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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re application of ZUCKER, Jerry	)	
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For: MELT BLOWN BATTERY SEPARATOR	)	Attorney Docket: 156-0223

THIRD PARTY SUBMISSION IN PUBLISHED APPLICATION UNDER 37 CFR §1.99

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Sir:

The undersigned attorney respectfully submits the publication listed below in the above-captioned application; a check in the amount of $180 is enclosed to pay the fee for this submission.

Publication submitted

U.S. Patent No. 6,114,017, Fabbricante et al., September 5, 2000

U.S. Patent No. 5,679,379, Fabbricante et al., October 21, 1997

Velu, Yogeshwar; Farer, Raoul; Ghosh, Tushar; and Seyam, Abdelfattah, "FORMATION OF SHAPED/MOLDED MELTBLOWING NONWOVEN STRUCTURES", *Journal of Textile and Apparel, Technology and Management*, Volume 1, Issue 1, pages 1-13, September, 2000.

Gahan, Richard and Zguris, George C., "A Review of the Melt Blown Process", The Fifteenth Annual Battery Conference on Applications and Advances, pages 145-, January 11-14, 2000

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US006114017A

United States Patent [19]

Fabbricante et al.

[11] Patent Number: 6,114,017

[45] Date of Patent: Sep. 5, 2000

[54] MICRO-DENIER NONWOVEN MATERIALS MADE USING MODULAR DIE UNITS

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[21] Appl. No.: **08/899,125**

[22] Filed: **Jul. 23, 1997**

[51] **Int. Cl.**^{7} **B32B 27/14**; D04H 3/16

[52] **U.S. Cl.** **428/198**; 428/219; 156/167

[58] **Field of Search** 156/167; 428/198, 428/219

[56] **References Cited**

U.S. PATENT DOCUMENTS

4,375,718 3/1983 Wadsworth et al. .... 29/592 E

5,232,770 8/1993 Joseph 428/284

Primary Examiner—Christopher Raimund

[57] **ABSTRACT**

A series of nonwoven webs and the processes for their production are disclosed. The resultant webs have equal or superior strength characteristics to conventional nonwoven fabrics made using spunbond processes but their constituent fibers are of a finer diameter. This is accomplished through a process of melt blowing a nonwoven fabric made from at least one polymer at low polymer flows per die hole and low air and polymer pressures using modular die technology to provide a die with one or more rows of die holes. The nonwoven fabric of this invention may be used in products such as diapers, feminine hygiene products, filters, progressive layer filters, adult incontinence products, wound dressings, bandages, sterilization wraps, surgical drapes, geotextiles, wipers, insulation and other related products.

19 Claims, 2 Drawing Sheets

Fig. 1

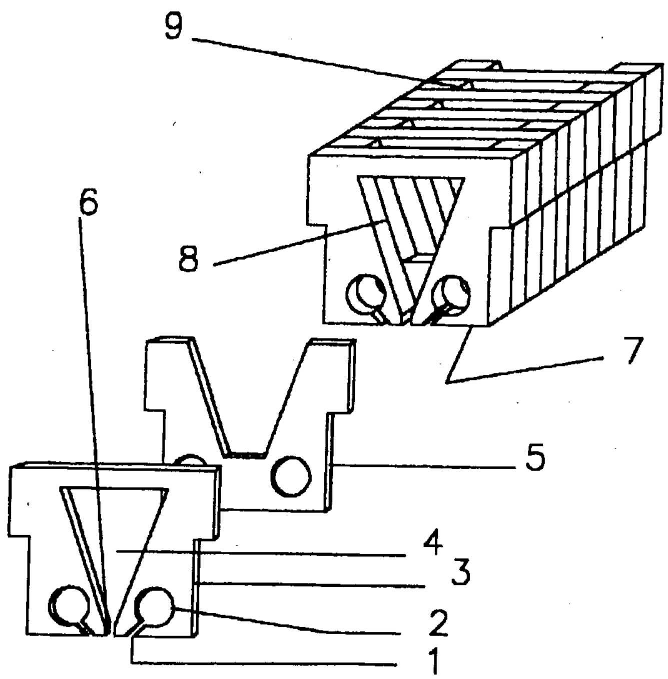

Fig. 2

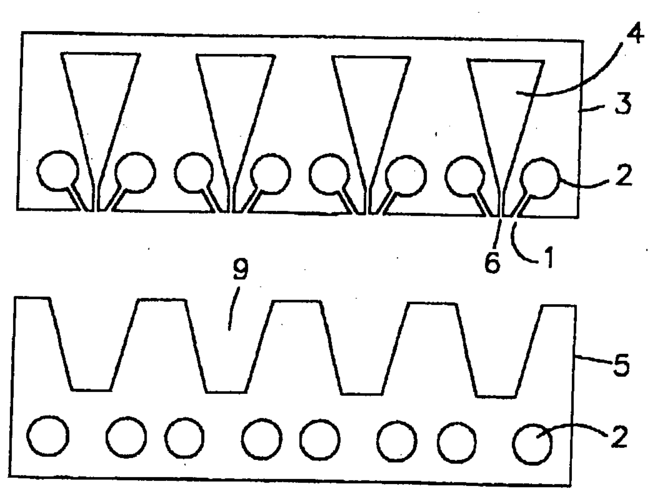

Fig. 4

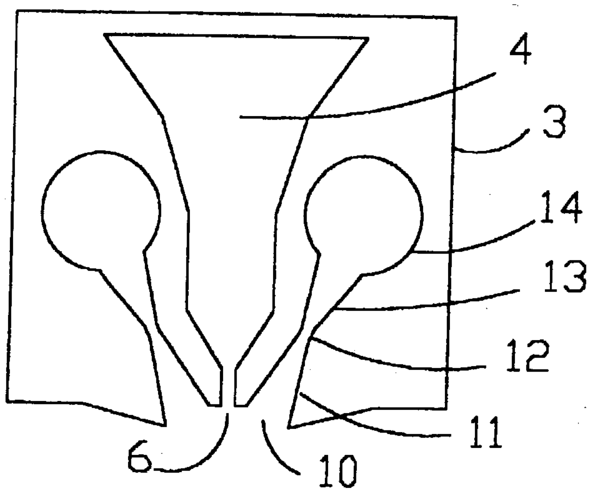
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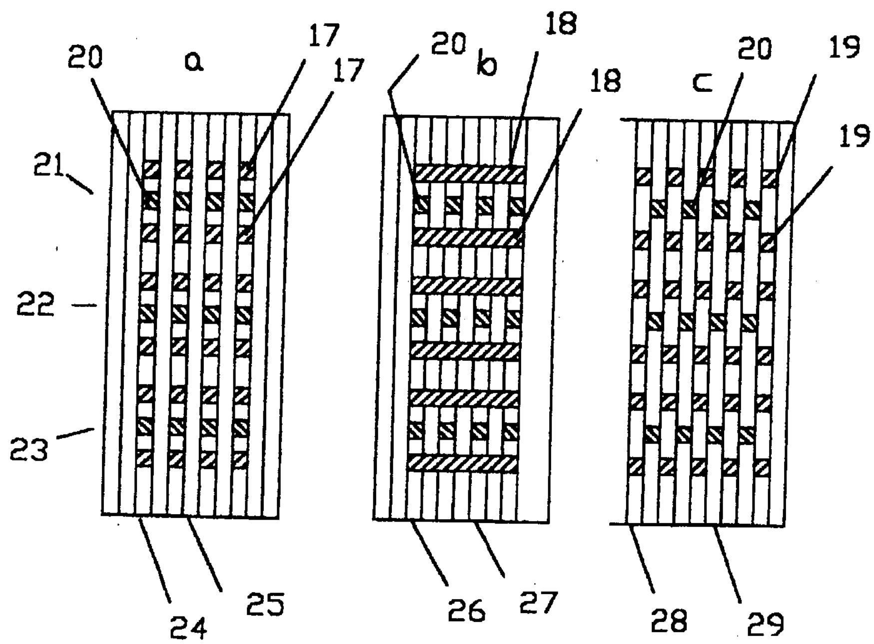
Fig. 3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MICRO-DENIER NONWOVEN MATERIALS MADE USING MODULAR DIE UNITS

FIELD OF THE INVENTION

The present invention relates to micro-denier nonwoven webs and their method of production using modular die units in an extrusion and blowing process.

DESCRIPTION OF THE PRIOR ART

Thermoplastic resins have been extruded to form fibers and webs for many years. The nonwoven webs so produced are commercially useful for many applications including diapers, feminine hygiene products, medical and protective garments, filters, geotextiles and the like.

A highly desirable characteristic of the fibers used to make nonwoven webs for certain applications is that they be as fine as possible. Fibers with small diameters, less than 10 microns, result in improved coverage and higher opacity. Small diameter fibers are also desirable since they permit the use of lower basis weights or grams per square meter of nonwoven. Lower basis weight, in turn, reduces the cost of products made from nonwovens. In filtration applications small diameter fibers create correspondingly small pores which increase the filtration efficiency of the nonwoven

The most common of the polymer-to-nonwoven processes are the spunbond and meltblown processes. They are well known in the US and throughout the world. There are some common general principles between melt blown and spunbond processes. The most significant are the use of thermoplastic polymers extruded at high temperature through small orifices to form filaments and using air to elongate the filaments and transport them to a moving collector screen where the fibers are coalesced into a fibrous web or nonwoven.

In the typical spunbond process the fiber is substantially continuous in length and has a fiber diameter typically in the range of 20 to 80 microns. The meltblown process, on the other hand, typically produces short, discontinuous fibers that have a fiber diameter of 2 to 6 microns.

Commercial meltblown processes, as taught by U.S. Pat. No. 3,849,241 to Buntin, et al, use polymer flows of 1 to 3 grams per hole per minute at extrusion pressures from 400 to 1000 psig and heated high velocity air streams developed from an air pressure source of 60 or more psig to elongate and fragment the extruded fiber. This process also reduces the fiber diameter by a factor of 190 (diameter of the die hole divided by the average diameter of the finished fiber) compared to a diameter reduction factor of 30 in spunbond processes. The typical meltblown die directs air flow from two opposed nozzles situated adjacent to the orifice such that they meet at an acute angle at a fixed distance below the polymer orifice exit. Depending on the air pressure and velocity and the polymer flow rate the resultant fibers can be discontinuous or substantially continuous. In practice, however, the continuous fibers made using accepted meltblown art and commercial practice are large diameter, weak and have no technical advantage. Consequently the fibers in commercial meltblown webs are fine (2–10 microns in diameter) and short, typically being less than 0.5 inches in length.

It is well known in the nonwoven industry that, in order to be competitive in melt blowing polymers, from both an equipment and a product standpoint, polymer flows per hole must be at least 1 gram per minute per hole as disclosed by U.S. Pat. No. 5,271,883 to Timmons et al. If this is not the

case additional dies or beams are required to produce nonwovens at a commercially acceptable rate. Since the body containing the die tips and the die tips themselves as used in standard commercial melt blowing die systems are very expensive to produce, multiple die bodies make low polymer and low air flow systems unworkable from an operational and an economic viewpoint. It is additionally recognized that the high air velocities coupled with the very large volumes of air created in a typical meltblown system creates considerable turbulence around the collector. This turbulence prevents the use of multiple rows of die holes especially if for technical or product reasons the collector is very close to the die holes. Additionally, the extremely high cost of machining makes multiple rows of die holes enclosed in a single die body cost prohibitive. Presently the art of blowing or drawing fibers, composed of the various thermally extrudable organic and inorganic materials, is limited to the use of subsonic air flows although the achievement of supersonic flows would be advantageous in certain meltblown and spunbond applications. It is well known from fluid dynamics, however, that in order to develop supersonic flows in compressible fluids, such as air, a specially designed convergent-divergent nozzle must be used. However, it is virtually impossible to provide the correct convergent-divergent profile for a nozzle by machining a monolithic die especially when large numbers of nozzles are required in a small space.

SUMMARY OF THE INVENTION

The instant invention is a new method of making nonwoven webs, mats or fleeces wherein a multiplicity of filaments are extruded at low flows per hole from a single modular die body or a series of modular die bodies wherein each die body contains one or more rows of die tips. The modular construction permits each die hole to be flanked by up to eight air jets depending on the component plate design of the modular die.

The air used in the instant invention to elongate the filaments is significantly lower in pressure and volume than presently used in commercial applications. The instant invention is based on the surprising discovery that using the modular die design, in a melt blowing configuration at low air pressure and low polymer flows per hole, continuous fibers of extremely uniform size distribution are created, which fibers and their resultant unbonded webs exhibit significant strength compared to typical unbonded meltblown or spunbond webs. In addition substantial self bonding is created in the webs of the instant invention. Further, it is also possible to create discontinuous fibers as fine as 0.1 microns by using converging-diverging supersonic nozzles.

For purposes of defining the air flow characteristics of the instant invention the term "blowing" is assumed to include blowing, drafting and drawing. In the typical spunbond system the only forces available to elongate the fiber as it emerges from the die hole is the drafting or drawing air. This flow is parallel to the fiber path. In the typical meltblown system the forces used to elongate the fiber are directed at an oblique angle incident to the surface. The instant invention uses air to produce fiber elongation by forces both parallel to the fiber path and incident to the fiber path depending on the desired end result.

Accordingly, it is an object of the present invention to produce a unique nonwoven web using the modular extrusion die apparatus described in the U.S. application Ser. No. 08/370,383 by Fabbricante, et al now U.S. Pat. No. 5,679,379, whereby specially shaped plates are combined in a

repeating series to create a sequence of readily and economically manufactured modular die units which are then contained in a die housing which is a frame or holding device that contains the modular plate structure and accommodates the design of the molten polymer and heated air inlets. The cost of a die produced from that invention is approximately 10 to 20% of the cost of an equivalent die produced by traditional machining of a monolithic block. It is also critical to note that it is virtually impossible to machine a die having multiple rows of die holes and multiple rows of air jets.

Because of the modular die invention and its inherent economies of manufacture it is possible for multiple rows of die holes and multiple die bodies to be used without high capital costs. This in turn permits low flows per hole with concomitant ability to use low melt pressures for fiber extrusion and low air pressures for elongating these filaments. As an example, in an experimental meltblown die configuration, flows of less than 0.1 grams per hole per minute and using heated air at 5 psig pressure create a strong self bonded web of 2 micron fibers. The web may also be thermally bonded to provide even greater strength by using conventional hot calendering techniques where the calender rolls may pattern engraved or flat.

Another unexpected result is that because of the low pressure air and low flow volumes, even though the die bodies contains multiple rows of die tips, there is virtually no resultant turbulence that would create fiber entanglement and create processing problems.

A further unforeseen result of the instant invention is that the combination of multiple rows of die holes with multiple offset air jets all running at low polymer and air pressure do not create polymer and air pressure balancing problems within the die. Consequently the fiber diameter, fiber extrusion characteristics and web appearance are extremely uniform.

A further invention is that the web produced has characteristics of a meltblown material such as very fine fibers (from 0.6 to 8 micron diameter), small inter-fiber pores, high opacity and self bonding, but surprisingly it also has characteristics of a spunbond material such as substantially continuous fibers and high strength when bonded using a hot calender

A further invention is that when a die using a series of converging-diverging nozzles, either in discrete air jets or continuous slots which are capable of producing supersonic drawing velocities, wherein the flow of the nozzles is parallel to the centerline of the die holes, which die holes have a diameter greater than 0.015 inches, the web produced without the use of a quench air stream has fine fibers (from 5 to 20 microns in diameter dependent on die hole size, polymer flow rates and air pressures), small inter-fiber pores, good opacity and self bonding but, surprisingly, it has characteristics of a spunbond material such as substantially continuous fibers and high strength when bonded using hot calender. It is important to note that a quench stream can easily be incorporated within the die configuration if required by specific product requirements.

A further invention is that when a die using a series of converging-diverging nozzles, which are capable of producing supersonic drawing velocities, wherein the angle formed between the axis of the die holes and supersonic air nozzles varies between 0° and 60°, and which die holes have a diameter greater than 0.005 inches, the web produced has fine fibers (from 0.1 to 2 microns in diameter dependent on die hole size, polymer flow rates and air pressures), extremely small inter-fiber pores, good opacity and self bonding.

DESCRIPTION OF THE INVENTION

The present invention is a novel method for the extrusion of substantially continuous filaments and fibers using low polymer flows per die hole and low air pressure resulting in a novel nonwoven web or fleece having low average fiber diameters, improved uniformity, a narrow range of fiber diameters, and significantly higher unbonded strength than a typical meltblown web. When the material is thermally point bonded it is similar in strength to spunbonded nonwovens of the same polymer and basis weight. This permits the manufacture of commercially useful webs having a basis weight of less than 12 grams/square meter.

Another important feature of the webs produced are their excellent liquid barrier properties which permit the application of over 50 cm of water pressure to the webs without liquid penetration.

Another feature of the present invention is that the modular die units may be mixed within one die housing thus simultaneously forming different fiber diameters and configurations which are extruded simultaneously, and when accumulated on a collector screen or drum provide a web wherein the fiber diameters can be made to vary along the Z axis or thickness of the web (machine direction being the X axis and cross machine direction being the Y axis) based on the diameters of the die holes in the machine direction of the die body.

Yet another feature of the present invention is that multiple extrudable materials may be utilized simultaneously within the same extrusion die by designing multiple polymer inlet systems.

Still another feature of the present invention is that since multiple extrudable molten thermoplastic resins and multiple extrusion die configurations may be used within one extrusion die housing, it is possible to have both fibers of different material and different fiber diameters or configurations extruded from the die housing simultaneously.

The novel features which are considered characteristic for the invention are set forth in particular in the appended claims. The invention itself, however, both as to its construction and its method of operation, together with additional objects and advantages thereof, will be best understood from the following description of the specific embodiments when read in connection with the accompanying drawings.

It will be understood that each of the elements described above, or two or more together, may also find a useful application in other types of constructions differing from the type described above including but not limited to webs derived from thermoplastic polymers, thermoelastic polymers, glass, steel, and other extrudable materials capable of forming fine fibers of commercial and technical value.

BRIEF DESCRIPTION OF THE DRAWINGS

These features as well as others, shall become readily apparent after reading the following description in conjunction with the accompanying drawings in which:

FIG. 1 is a sectional view illustrating the primary plate and secondary plate that illustrates the arrangement of the various feed slots where there is both a molten thermoplastic resin flow and an air flow through the modular die and both the polymer die hole and the air jet are contained in the primary plate.

FIG. 2 shows how primary and secondary die plates in the modular plate construction can be used to provide 4 rows of die holes and the required air jet nozzles for each die hole.

FIG. 3 is a plan view of three variations on the placement of die holes and their respective air jet nozzles in a die body with 3 rows of die holes in the cross-machine direction.

FIG. 4 illustrates the incorporation of a converging-diverging supersonic nozzle in a primary modular die plate for the production of supersonic air or other fluid flows.

DETAILED DESCRIPTION OF SOME OF THE PREFERRED EMBODIMENTS

The melt blown process typically uses an extruder to heat and melt the thermopolymer. The molten polymer then passes through a metering pump that supplies the polymer to the die system where it is fiberized by passage through small openings in the die called, variously, die holes, spinneret, or die nozzles. The exiting fiber is elongated and its diameter is decreased by the action of high temperature blowing air. Because of the very high velocities in standard commercial meltblowing the fibers are fractured during the elongation process. The result is a web or mat of short fibers that have a diameter in the 2 to 10 micron range depending on the other process variables such as hole size, air temperature and polymer characteristics including melt flow, molecular weight distribution and polymeric species.

Referring to FIG. 1 of the drawings a modular die plate assembly 7 is formed by the alternate juxtaposition of primary die plates 3 and secondary die plates 5 in a continuing sequence. A fiber forming, molten thermoplastic resin is forced under pressure into the slot 9 formed by secondary die plate 5 and primary die plate 3 and secondary die plate 5. The molten thermoplastic resin, still under pressure, is then free to spread uniformly across the lateral cavity 8 formed by the alternate juxtaposition of primary die plates 3 and secondary die plates 5 in a continuing sequence. The molten thermoplastic resin is then extruded through the orifice 6, formed by the juxtaposition of the secondary plates on either side of primary plate 3, forming a fiber. The size of the orifice that is formed by the plate juxtaposition is a function of the width of the die slot 6 and the thickness of the primary plate 3. The primary plate 3 in this case is used to provide two air jets 1 adjacent to the die hole. It should be recognized that the secondary plate can also be used to provide two additional air jets adjacent to the die hole.

The angle formed between the axis of the die hole and the air jet slot that forms the air nozzle or orifice 6 can vary between 0° and 60° although in this embodiment a 30° angle is preferred. In some cases there may be a requirement that the exit hole be flared.

Referring to FIG. 2 this shows how the modular primary and secondary die plates are designed to include four rows of die holes and air jets. The plates are assembled into a die in the same manner as shown in FIG. 1.

Referring to FIG. 3 we see a plan view of the placement of die holes and air jet nozzles in three different die bodies FIGS. 3*a*, 3*b* and 3*c* each with 3 rows 21, 22, 23 of die holes and air jets in the machine direction of the die. The result is a matrix of air nozzles and melt orifices where their separation and orientation is a function of the plate and slot design and primary and secondary plate(s) thickness. FIG. 3*a* shows a system wherein the die holes 20 and the air jets 17 are located in the primary plate 24 with the secondary plate 25 containing only the polymer and air passages. In this embodiment each die hole along the width of the die assembly has eight air jets immediately adjacent to it. Two jets in each primary plate impinge directly upon the fiber exiting the die hole while the other six assist in drawing the fiber with an adjacent flow.

FIG. 3*b* shows a system wherein the die holes 20 are located only in the primary plate and the air jets are located in both the primary 26 and secondary plates 27 thereby creating a continuous air slot 18 on either side of the row of die holes.

FIG. 3*c* shows a system wherein the die holes 20 are located only in the primary plate 28 and the air jets are located in the secondary plates 29 thereby creating airjets 19 on either side of the row of die holes. This adjacent flow draws without impinging directly on the fiber and assists in preserving the continuity of the fiber without breaking it. This configuration provides four air jets per die hole.

While it is not shown, it is clear from the above that a juxtaposed series of only primary plates would provide a slit die that could be used for film forming.

Consequently the instant invention presents the ability to extend the air and melt nozzle matrix a virtually unlimited distance in the lateral and axial directions. It will be apparent to one versed in the art how to provide the polymer and air inlet systems to best accommodate the particular system being constructed. The modular die construction in this particular embodiment provides a total of 4 air nozzles for blowing adjacent to each die hole although it is possible to incorporate up to 8 nozzles adjacent to each die hole. The air, which may be at temperatures of up to 900° F., provides a frictional drag on the fiber and attenuates it. The degree of attenuation and reduction in fiber diameter is dependent on the melt temperature, die pressure, air pressure, air temperature and the distance from the die hole exit to the surface of the collector screen.

It is well known in the art that very high air velocities will elongate fibers to a greater degree than lower velocities. Fluid dynamics considerations limit slot produced air velocities to sonic velocity. Although it is known how to produce supersonic flows with convergent-divergent nozzles this has not been successfully accomplished in meltblown or spunbond technology. It is believed that this is due to the considerable difficulty or impossibility of producing a large number of convergent-divergent nozzles in a small space in conventional monolithic die manufacturing.

FIG. 4 illustrates how this can be accomplished within the modular die plate configuration. Only a primary plate 3 is shown. In practice the secondary plate would be similar to that shown in FIG. 1. The primary plate contains a die hole 6 and two converging-diverging nozzles. FIG. 4 shows how the lateral air passage 14 provides pressurized air to the converging duct section 13 which ends in a short orifice section 12 connected to the diverging duct section 11 and provides, in this case, two incident supersonic flows impinging on the fiber exiting the die hole. This arrangement provides very high drafting and breaking forces resulting in very fine (less than 1 micron diameter) short fibers.

This general method of using modular dies to create a multiplicity of convergent-divergent nozzles can also be used to create a supersonic flow within a conventional slot draw system as currently used in spunbond by using an arrangement wherein the converging-diverging nozzles are parallel to the die hole axis rather than inclined as shown in FIG. 4. An alternative to the two air nozzles per die hole arrangement is to use the nozzle arrangement of FIG. 3*b* wherein the primary and secondary plates all contain converging-diverging nozzles resulting in a continuous slot converging-diverging nozzle.

In the typical meltblown application the extrusion pressure is between 400 and 1000 pounds per square inch. This pressure causes the polymer to expand when leaving the die

hole because of the recoverable elastic shear strain peculiar to viscoelastic fluids. The higher the pressure, the greater the die swell phenomena. Consequently at high pressures the starting diameter of the extrudate is up to 25% larger than the die hole diameter making fiber diameter reduction more difficult. In the instant embodiment the melt pressure typically ranges from 20 to 200 psig. The specific pressure depends on the desired properties of the resultant web. Lower pressures result in less die swell which assists in further reduction of finished fiber diameters.

The attenuated fibers are collected on a collection device consisting of a porous cylinder or a continuous screen. The surface speed of the collector device is variable so that the basis weight of the product web can increased or decreased. It is desirable to provide a negative pressure region on the down stream side of the cylinder or screen in order to dissipate the blowing air and prevent cross currents and turbulence.

The modular design permits the incorporation of a quench air flow at the die in a case where surface hardening of the fiber is desirable. In some applications there may be a need for a quench air flow on the fibers collected on the collector screen.

any other method known in the art. The laminate may also be made in-situ wherein a spunbond web is applied to one or both sides of the fabric of this invention and the layers are bonded by point bonding using a thermal calender or any other method known in the art.

EXAMPLES

Several self bonded nonwoven webs were made from a meltblowing grade of Philips, 35 melt flow polypropylene resin using a modular die containing a single row of die holes. The length of a side of the square spinneret holes was 0.015 inches and the flow per hole varied from 0.05 to 0.1 grams/hole/minute at 150 psig. Air pressure of the heated air flow was varied from 4 to10 psig. Fiber diameter, web strength and hydrostatic head (inches of water head) were measured. The fibers were collected on a collector cylinder capable of variable surface speed.

TABLE 1

Trial Run	Air Pressure	Flow Rate	Basis Wt	Microns	H2O head	Break Load
1	4	0.05	10.3	2.7	20	241
2	4	0.10	17.8	2.9	>30	456
3	6	0.05	11.7	2.2	>30	299
4	6	0.10	16.5	2.7	>30	423
5	10	0.05	12.1	1.9	>30	270

Ideally the distance from the die hole outlet to the surface of the collector should be easily varied. In practice the distance generally ranges from 3 to 36 inches. The exact dimension depends on the melt temperature, die pressure, air pressure and air temperature as well as the preferred characteristics of the resultant fibers and web.

The resultant fibrous web may exhibit considerable self bonding. This is dependent on the specific forming conditions. If additional bonding is required the web may be bonded using a heated calender with smooth calender rolls or point bonding.

The method of the invention may also be used to form an insulating material by varying the distance of the collector

The results shown in Table 1 show that the method of the invention unexpectedly produced a novel web state with significant self bonding with surprising strength in the unbonded and with excellent liquid barrier properties.

In another example several self bonded nonwoven webs of were made from a meltblowing grade of Philips polypropylene resin using a die with three rows of die holes across the width of the die. The length of a side of the square spinneret holes was 0.015 inches and the flow per hole varied from 0.05 to 0.1 grams/hole/minute at 150 psig. Air pressure of the heated air flow was varied from 4 to 10 psig. The fibers were collected on a collector cylinder capable of variable surface speed. Fiber diameter, web strength and hydrostatic head (inches of water head) were measured.

TABLE 2

Trial Run	Air Pressure	Flow Rate	Basis Wt	Microns	H2O head	Break Load
6	5	0.11	34.6	2.9	>45	847
7	4.5	0.10	25.4	3.0	>45	671
8	6	0.10	30	2.5	>45	815

means from the die resulting in a low density web of self-bonded fibers with excellent resiliency after compression.

The fabric of this invention may be used in a single layer embodiment or as a multi-layer laminate wherein the layers are composed of any combination of the products of the instant invention plus films, woven fabrics, metallic foils, unbonded webs, cellulose fibers, paper webs both bonded and debonded, various other nonwovens and similar planar webs suitable for laminating. Laminates may be formed by hot melt bonding, needle punching, thermal calendering and

The results shown in Table 2 unexpectedly show that the method of the invention produced a novel web with surprising strength in the unbonded state and with excellent liquid barrier properties.

In still another example self bonded nonwoven webs were made from a meltblowing grade of Philips polypropylene resin in a modular die containing a single row of die holes. In this case the drawing air was provided from four converging-diverging supersonic nozzles per die hole. The converging-diverging supersonic nozzles were placed such that their axes were parallel to the axis of the die hole. The

angle of convergence was 7° and the angle of divergence was 7°. The length of a side of the square spinneret holes was 0.025 inches and the polymer flow per hole was 0.2 grams/hole/minute at 250 psig. Air pressure was 15 psig. The fibers were collected on a collector cylinder capable of variable surface speed. A quench air stream was directed on to the collector. Fiber diameter and web strength were measured.

TABLE 3

Trial Run	Air Pressure	Flow Rate	Basis Wt	Microns	Break Load
9	15	0.25	15.3	12.1	548

The results shown in table 3 demonstrate that the method of the invention produced a novel web with surprising strength in the unbonded state and continuous fibers and a web appearance similar to spunbond material. Microscopic examination of the resultant webs showed excellent uniformity, no shot and no evidence of twinned fibers or fiber bundles and clumps due to turbulence.

In yet another example self bonded nonwoven webs were made from a meltblowing grade of Philips polypropylene resin in a modular die containing a single row of die holes. In this case the drawing air was provided from four converging-diverging supersonic nozzles per die hole. The converging-diverging supersonic nozzles were inclined at a 60° angle to the axis of the die hole. The length of a side of the square spinneret holes was 0.015 inches and the flow per hole was 0.11 grams/hole/minute at 125 psig. Air pressure of the air flow was 15 psig. The fibers were collected on a collector cylinder capable of variable surface speed. Fiber diameter and web strength were measured. These results are shown in Table 4.

TABLE 4

Trial Run	Air Pressure	Flow Rate	Basis Wt	Microns	Break Load
10	15	0.11	25.3	0.5	622

The results show that the method of the invention produced a novel web with surprisingly small diameter fibers, adequate strength in the unbonded state and a mix of continuous and discontinuous fibers. Microscopic examination of the resultant webs showed excellent uniformity and no evidence of twinned fibers or fiber bundles and clumps due to turbulence.

While the invention has been illustrated and described as embodied in an extrusion apparatus with modular die units which produces a unique web with properties of spunbond and meltblown, it is not intended to be limited to the details shown, since it will be understood that various omissions, modifications, substitutions and changes in the forms and details of the devices illustrated and in their operation can be made by those skilled in the art without departing in any way from the spirit of the present invention.

Without further analysis, the foregoing will so fully reveal the essence of the present invention that others can, by applying current knowledge, readily adapt it for various applications without omitting features that, from the standpoint of prior art, fairly constitute essential characteristics of the generic or specific aspects of this invention.

We claim:

1. A method for manufacturing a nonwoven web which comprises:

melting a polymer by polymer heating and extrusion means;

extruding said polymer at flow rates of less than 1 gram per minute per hole through the polymer orifices of one or more modular dies, each of said dies consisting of two or more spaced apart cross directional rows of polymer orifices, wherein the diameters of said polymer orifices of each individual row are constant diameter and wherein each successive row of said polymer orifices has a smaller diameter, said die being heated by a heating means; and

blowing said polymer extrudate, using heated air of at least 200° F. or more, from 2 or more air jets per polymer orifice, wherein said air jets may have a constant or a variable cross-section, to produce essentially continuous polymer filaments wherein said continuous polymer filaments from each row on the die have different and increasingly smaller diameters than the preceding rows, and depositing said fiberized polymer on a collecting means to form a self bonded web consisting of as many layers of disbursed continuous polymer filaments as the number of rows in the die wherein each layer consists of filaments having a different and smaller diameter resulting in a filament size gradient through its depth.

2. The method of claim 1 wherein two or more polymer manifolds are used to supply different polymers to each of said polymer orifice rows.

3. The method of claim 1 wherein said fibers range from 0.1 microns to 5 microns.

4. The nonwoven web produced according to the method of claim 1 where the web is thermally bonded.

5. The method of claim 1, wherein said variable cross section air jet is a converging-diverging nozzle.

6. The method of claim 5 wherein the converging portion of said converging-diverging nozzle converges at an angle of no less than 2 degrees and no more than 18 degrees from the centerline of said nozzle; and the diverging portion of said nozzle diverges at an angle of no less than 3 degrees and no more than 18 degrees from the centerline of said nozzle.

7. The nonwoven fabric of claim 1 wherein said polymer is selected from the group consisting of olefins and their copolymers, styrenics and their copolymers, polyamides, polyesters and their copolymers, halogenated polymers, and thermoelastic polymers and their copolymers.

8. The nonwoven fabric produced according to the method of claim 1 where the web is a filtration material wherein the fibers of said web produced from each row of polymer orifices, which have progressively smaller diameters, are progressively smaller and range from 20 to 0.1 microns.

9. A method for manufacturing a nonwoven web which comprises:

melting a polymer by polymer heating and extrusion means;

extruding said polymer at flow rates of less than 1 gram per minute per hole through the polymer orifices of one or more modular dies, each of said dies consisting of two or more spaced apart cross directional rows of polymer orifices, wherein the diameters of said polymer orifices of each individual row are an equal and constant diameter and all rows have the same diameter polymer orifices, said die being heated by a heating means; and

blowing said polymer extrudate, using heated air of at least 200° F. or more, from 2 or more air jets per

polymer orifice, wherein said air jets may have a constant or a variable cross-section, to produce essentially continuous polymer filaments wherein said continuous polymer filaments from each row on the die are deposited on a collecting means to form a multi-layered self bonded web consisting of as many layers of disbursed continuous polymer filaments as the number of rows in the die.

10. The method of claim **9** wherein said variable cross section air jet is a converging-diverging nozzle.

11. The method of claim **10** wherein the converging portion of said converging-diverging nozzle converges at an angle of no less than 2 degrees from the centerline of said nozzle and no more than 18 degrees; and the diverging portion of said nozzle diverges at an angle of no less than 3 degrees and no more than 18 degrees from the centerline of said nozzle.

12. A low density insulation web produced according to the method of claim **9**.

13. The nonwoven web produced according to the method of claim **9** wherein a layer of spunbond material is deposited on one or both sides of said web and the resultant laminate is bonded using a thermal calender.

14. The nonwoven web produced according to the method of claim **9** wherein said fibers range from 0.1 microns to 10 microns.

15. A method for manufacturing a nonwoven web which comprises:

melting a polymer by polymer heating and extrusion means;

extruding said polymer into filaments at flow rates of less than 1 gram per minute per hole through the polymer orifices of a one or more modular dies, each of said dies consisting of two or more spaced apart cross directional rows of polymer orifices, wherein the diameters of said polymer orifices of each individual row are an equal and constant diameter and all rows have the same diameter polymer orifices, said die being heated by a heating means; and

blowing said polymer extrudate, using tempered air between 50° F. and 700° F. or more, from two or more two or more continuous converging-diverging nozzle slots, said nozzle slots being placed adjacent and essentially parallel to said polymer orifice exits wherein said continuous converging-diverging nozzle slots form a high speed air curtain on either side of, and essentially parallel to, the polymer extrudate, whereby said high speed air curtain attenuates said filaments and said continuous polymer filaments from each row on said die are deposited on a collecting means to form a multi-layered self bonded web consisting of as many layers of disbursed continuous polymer filaments as the number of said rows of polymer orifices in said die.

16. The method of claim **15** wherein said high speed air curtains may be separated from said high speed air curtains of any adjacent polymer orifice rows by plates positioned perpendicular to the surface of said modular die and parallel to said polymer orifice rows wherein said plates form a discrete channel for the drawing of said extrudate.

17. The nonwoven web produced according to the method of claim **15** where the web is thermally bonded.

18. The method of claim **15** wherein said high speed air curtain attenuates the continuous polymer filaments for the drawing of said extrudate.

19. The method of claim **15** wherein the converging portion of said converging-diverging nozzle converges at an angle of no less than 2 degrees from the centerline of said nozzle and no more than 18 degrees; and the diverging portion of said nozzle diverges at an angle of no less than 3 degrees and no more than 18 degrees from the centerline of said nozzle.

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United States Patent [19]

Fabbricante et al.

[11] **Patent Number: 5,679,379**

[45] **Date of Patent: Oct. 21, 1997**

[54] **DISPOSABLE EXTRUSION APPARATUS WITH PRESSURE BALANCING MODULAR DIE UNITS FOR THE PRODUCTION OF NONWOVEN WEBS**

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[21] Appl. No.: **370,383**

[22] Filed: **Jan. 9, 1995**

[51] **Int. Cl.**^{6} **B29C 39/22**

[52] **U.S. Cl.** .... **425/7**; 425/72.2; 425/192 S; 425/463; 425/464

[58] **Field of Search** .... 425/133.5, 131.5, 425/192 S, 72.2, 186, 463, 382.2, 7, 464; D16/217; 264/211.4

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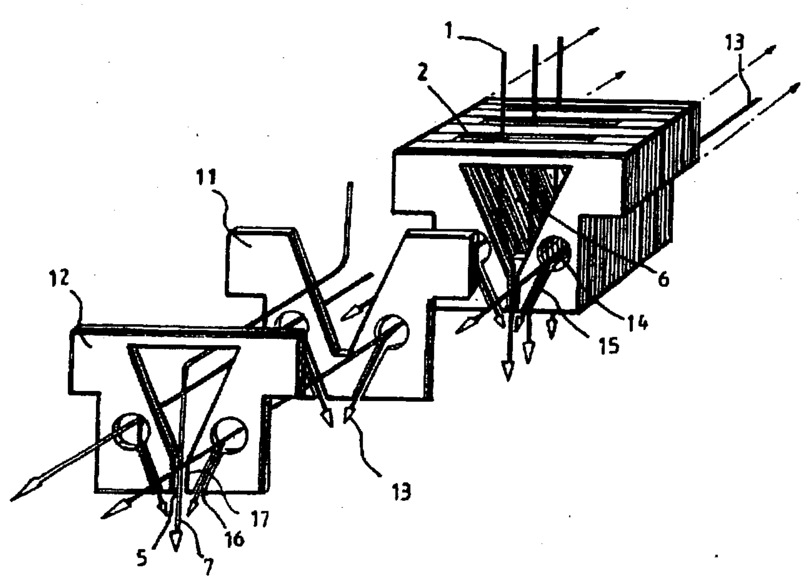
Primary Examiner—Thomas R. Weber

[57] **ABSTRACT**

The present invention relates to a die body consisting of a multiplicity of modular die plates, which are easily and rapidly interchangeable. The modular die plates can be configured to extrude different shapes and types of fibers. The apparatus may also be configured to extrude multiple types of materials each from a plurality of separate ports or from a plurality of common ports. The apparatus may also be designed to include single or multiple ports to direct air or other fluids to draw or attenuate the extrudate into fibers of a desired diameter. The extrudate may be treated with the air or various other gases or fluids within the die or exterior to the die tips.

9 Claims, 3 Drawing Sheets



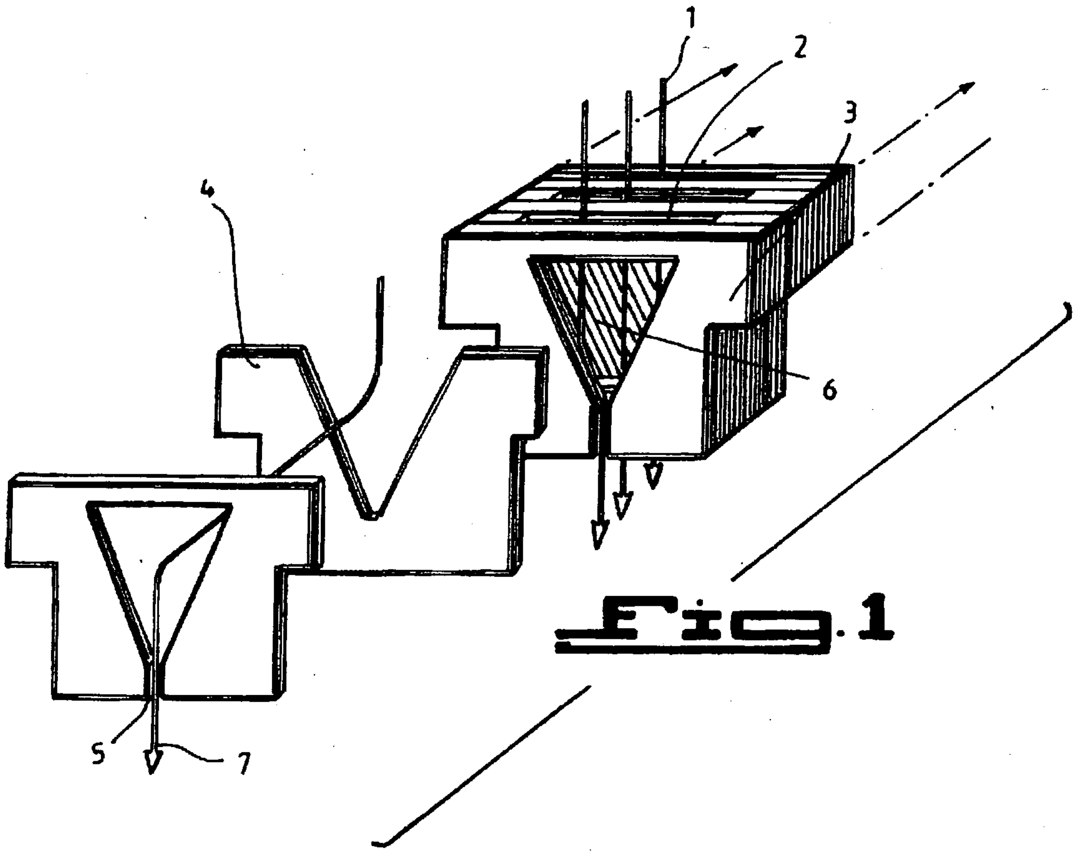


Fig. 1

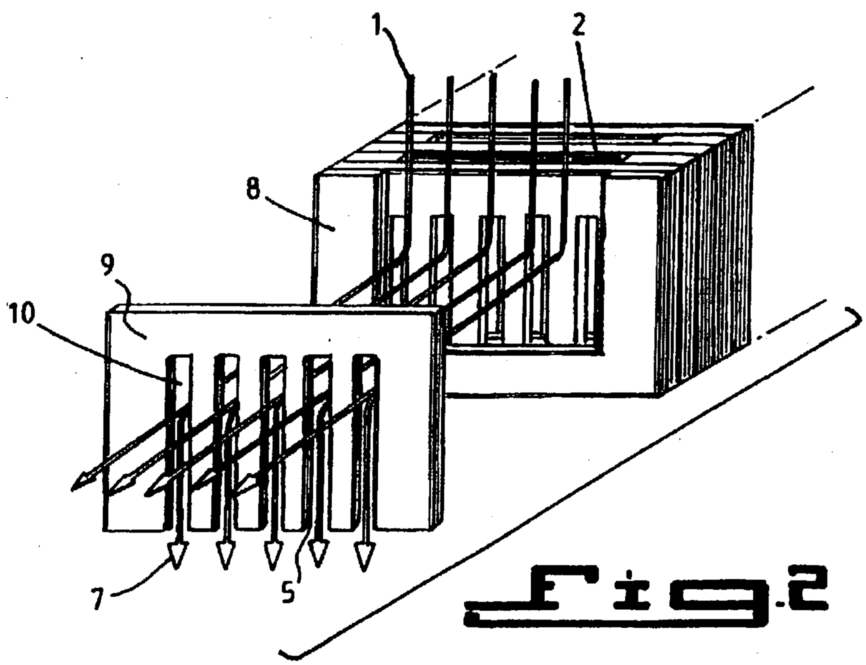


Fig. 2

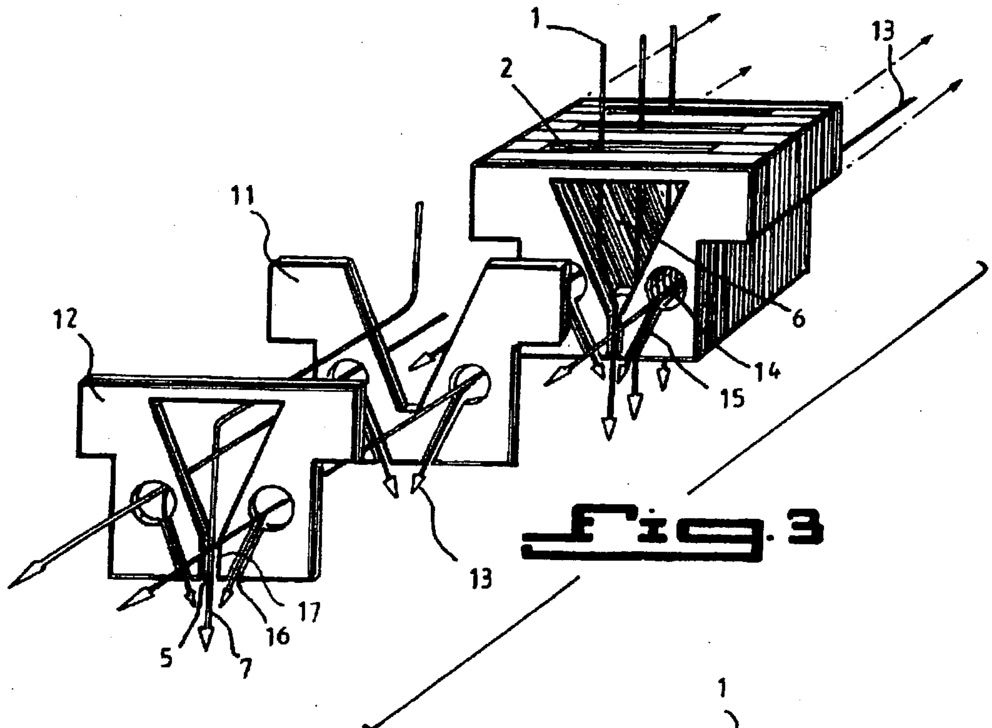


Fig. 3

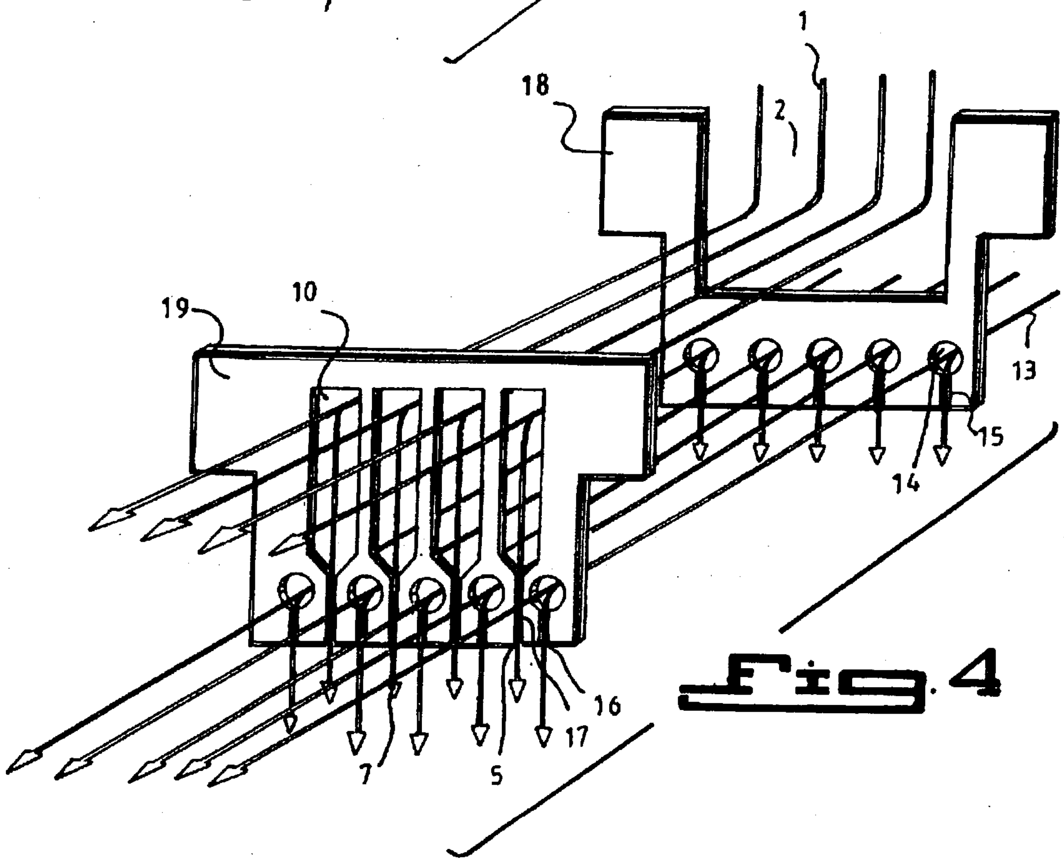


Fig. 4

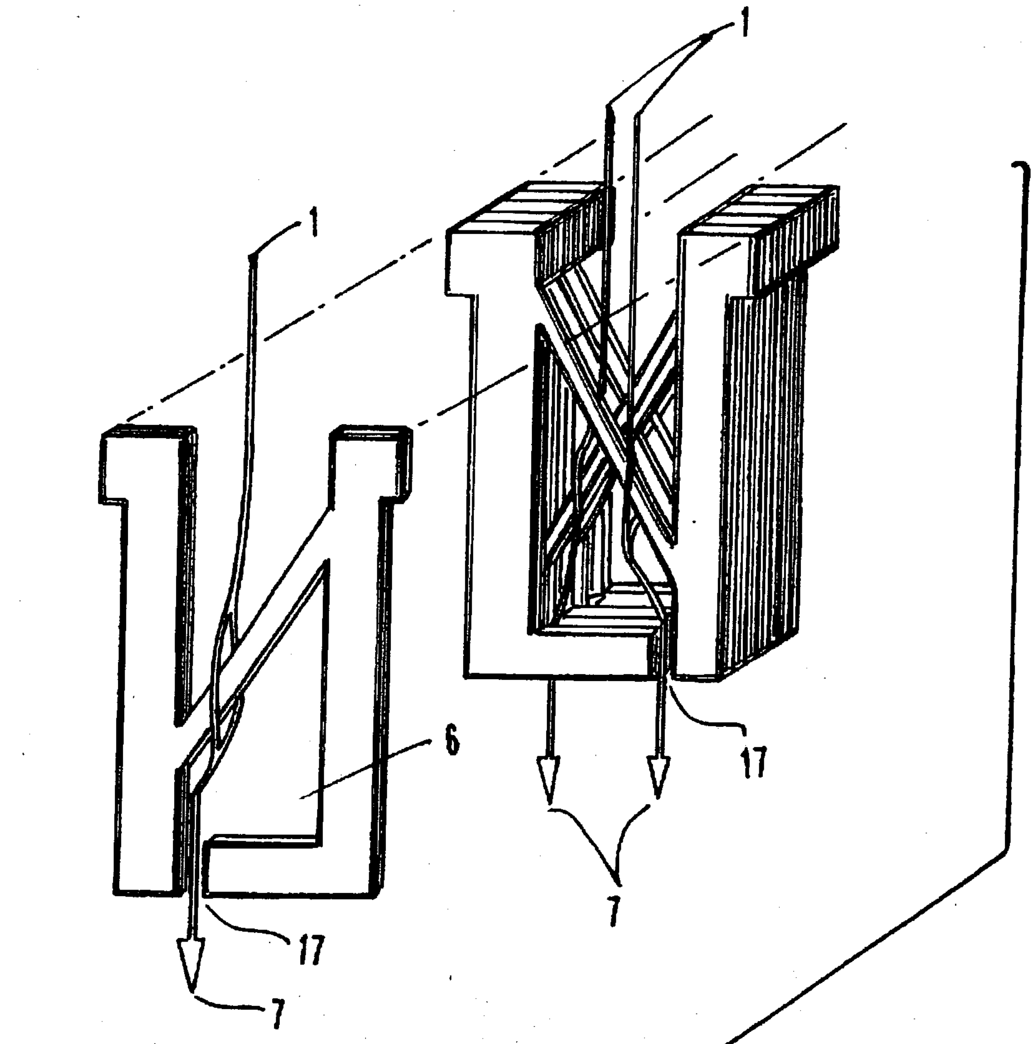


Fig. 5

DISPOSABLE EXTRUSION APPARATUS WITH PRESSURE BALANCING MODULAR DIE UNITS FOR THE PRODUCTION OF NONWOVEN WEBS

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to molten thermoplastic resin extrusion and particularly to an extrusion apparatus assembled from modular die units.

2. Description of the Prior Art

In the extrusion process a molten thermoplastic polymeric resin is directed through an extrusion die to form a fiber extrusion. Such fiber substrates may be oval, elliptical, square, rectangular, round, lobate, and the like in cross-section. The fiber extruded is typically continuous in length and of a constant cross section.

An extrusion die is typically made from a block of steel in which the various channels and die tips required for directing the flow of the molten polymer are machined or drilled. In order to reduce the degree of metal working needed, in many cases other machined blocks of steel are conjoined to the basic die body to carry the thermoplastic or other fluids required by the particular extrusion process. As extrusion dies grow larger and more complicated because of the use of multiple thermoplastic melts and drawing fluids, the complexity of machining increases geometrically as do the costs for manufacturing the die.

An additional factor that adds to the cost of using extrusion dies is the requirement that they be frequently cleaned of the residual deposits of carbonaceous matter that is created by the oxidation of the thermoplastics due to high temperature. This requires that additional dies be available for spares. Also dies have a limited life because of the erosion of the die tip tolerances due to the high temperatures and the wear of the fluids flowing through the dies under high pressures.

Numerous innovations of the extrusion die apparatus are described in the prior art for die design and construction. These innovations generally address specific individual purposes that are narrow in scope and application.

SUMMARY OF THE INVENTION

Accordingly, it is an object of the present invention to provide a modular extrusion die apparatus whereby specially shaped plates are confined in a repeating series to create a sequence of easily and economically manufactured modular die units which are contained in a die housing which is a frame or holding device that contains the modular structure and accommodates the design of the extrusion apparatus. The cost of a die produced from the present invention is less than 2 0% the cost of an equivalent die produced by traditional machining of a monolithic block. In addition, these modular die units can be easily removed for purposes of replacement, cleaning, or inserting a different shape die unit to produce another fiber configuration or fiber size.

The die housing construction can be mounted in a "fixed" or "spinning" structure to produce fibers. The modular die units can be clamped tight into die housing or another holding device or structure for easy insertion and removal. The die housing may contain heating elements and temperature sensing elements, such as thermocouple for purposes of heating and controlling temperatures of both the molten thermoplastic resin and housing. The heating elements may be contained within the modular plates.

The purpose of this fiber making die is to form continuous or discontinuous extruded fibers from any molten extrudable material. The apparatus is capable of forming fibers in a broad range of cross sections, such as from 2 to 100 microns, by adjusting process variables including, but not restricted, to temperature, pressure and air velocity.

DESCRIPTION OF THE INVENTION

The present invention is a novel method for manufacturing inexpensive modular extrusion dies for the extrusion of molten thermoplastic resins in sheets and fibers. It may also be used for melt blown and spun bond applications. The essence of the invention is the formation of modular die units using specially shaped plates which are combined in a repeating series to create a die which can be manufactured in any length and width required without complicated and expensive machining requirements. The design of each plate permits the inclusion of one or more die orifices for extruding polymer and one or more orifices or nozzles for directing the flow of the drawing fluid. These modular die units can be easily removed for purposes of replacement, cleaning or to insert a different shape die unit to produce another fiber configuration or fiber size.

The dimensions of the die tips or holes and air jets are controlled by varying the thicknesses of the primary and secondary plates that comprise the modular die units within the apparatus to produce different fiber sizes within the same die housing configuration. For example: assuming there are more than one row of die holes, the first row can have an opening equal to "X"; the second row equal to "Y"; etc. Similarly, varying modular die unit configurations can make different fiber sizes within the same operational manufacturing process.

The primary and secondary modular die plates can be easily installed into the die housing by alternating them in the required order and fixing them in place. The modular die plates can be clamped, bolted, brazed, riveted or welded and set into the die housing or the die segments can be loaded in a die housing for easy insertion and removal. The die housing construction can be mounted in a "fixed" or "spinning" structure.

The invention permits the openings in the modular die assembly to be arranged in closer proximity than in conventional construction of monolithic fiber extrusion dies. Consequently, this invention is capable of producing more fibers of varying shapes in a smaller area than current state of the art techniques. The segment cross sections, which produce the fibers, can vary in unlimited configurations and shapes.

This modular die construction is much less expensive to manufacture than conventional construction of monolithic fiber extrusion dies. Conventional or laser drilling, electron discharge machining are not necessary for making very small die holes.

The molten thermoplastic resin material enters the inlet port under the required pressure and temperature to move the material at the velocity necessary to force it through the cavities or channels formed by the juxtaposition of the modular die plates. An extruded fiber is formed as the material is forced under pressure through the modular die units and into the die holes or capillaries. When the fiber exits the die hole, a high velocity air stream forces the fiber to attenuate and form a fiber with the desired characteristics.

The die insert can be designed to have one or more air chambers separating the die segments, thereby permitting the use of two or more different molten thermoplastic resins

of similar melt temperatures, which can be fiberized together. The fibers thus created are entangled and are bonded.

Molten thermoplastic resins, either of like or of different polymeric character, can enter two or more cavities separately from each other and can thus can be extruded separately in a sequential manner. For example, a cyclical sequence, molten thermoplastic resin "A" will run for one time, then shut off, and then molten thermoplastic resin "B" runs for another time period, which in turn shuts off. These cycles can vary in time or in combination with each other. For example, separate molten thermoplastic resins combine with each other, with one shutting off before the other. The variations are limitless, particularly in the manufacturing of filters, when fine fibers could be "laid down" first with a coarse fiber mixed in together, and finished off with a coarse fiber at the end of the cycle.

The present invention includes an additional method of making a die tip by designing the secondary plate so that it can be used as a primary plate by reversing alternate secondary plates, thus creating individual passageways. Also utilizing the same concept, and by specific design, many more passageways can be made. In this method, which eliminates the primary plate, the material to be produced flows through the top and inner chamber of the segment.

Accordingly, it is an object of the present invention to provide a modular die body extrusion apparatus. More particularly, it is an object of the present invention to provide a modular die extrusion apparatus in which the dies are easily removable and interchangeable. Additionally it is an object of the present invention to give a cost effective method for incorporating air nozzles for attenuating fibers as an integral part of the modular die unit.

In keeping with these objects, and with others which will become apparent hereinafter, one feature of the present invention resides, briefly stated, in the invention's ability to utilize both hot and cold extrudable materials.

In accordance with another feature of the present invention, the fibers may vary in thickness and configuration depending upon the modular die units used in the extrusion die.

Another feature of the present invention is that the modular die units may be mixed within one die housing, thus forming multiple, different types of fibers simultaneously upon extrusion.

Yet another feature of the present invention is that multiple, extrudable materials may be utilized simultaneously within the same extrusion die.

Still another feature of the present invention is that since multiple, extrudable, molten, thermoplastic resins and multiple extrusion die configurations may be used within one extrusion die housing, it is possible to have both different material fibers and different fiber configurations extruded from the die housing simultaneously.

Still yet another feature of the present invention is that the modular extrusion die may be free-spinning in order that the fibers intertwine after extrusion to form a fibrous mat. More particularly, the present invention relates to an extrusion apparatus with modular die units encased within a magazine which may be easily removed for replacement and disposal, cleaning and changing of the modular die units.

The novel features, which are considered characteristic for the invention, are set forth in particular in the appended claims. The invention itself, however, both as to its construction and its method of operation, together with additional objects and advantages thereof, will be best understood from the following description of the specific embodiments when read in connection with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

These features, as well as others, shall become readily apparent after reading the following description in conjunction with the accompanying drawings in which:

FIG. 1 is a perspective view illustrating the embodiment of a simple primary and secondary plate modular die, showing the arrangement of the plates and the flow of the molten thermoplastic resin into and through the modular die into a single die tip.

FIG. 2 is a perspective view illustrating the embodiment of a simple primary and secondary plate modular die, showing the arrangement of the plates and the flow of the molten thermoplastic resin into and through the modular die into multiple die tips.

FIG. 3 is a perspective view illustrating the embodiment of a simple primary and secondary plate modular die, showing the arrangement of the plates where there is both a molten thermoplastic resin flow and an air flow through the modular die into a single die tip.

FIG. 4 is a sectional view illustrating the embodiment of a simple primary and secondary plate modular die, showing the arrangement of the plates where there is both a molten thermoplastic resin flow and an air flow through the modular die into multiple die tips; and

FIG. 5 is a sectional view showing the embodiment of a simple primary and secondary plate modular die illustrating the arrangement of the plates where the primary plate is alternately reversed to act as a secondary plate.

LIST OF REFERENCE NUMERALS UTILIZED IN THE DRAWINGS

1—molten thermoplastic resin
2—slot
3—secondary die plate
4—primary die plate
5—orifice
6—lateral cavity
7—fibrous form of molten thermoplastic resin
8—primary die plate of second embodiment
9—secondary die plate of second embodiment
10—parallel lateral cavities
11—primary die plate of third embodiment
12—secondary die plate of third embodiment
13—air or fluid
14—separate or isolated channels
15—slots
16—exit orifices or nozzles
17—resin channel
18—primary die plate of fourth embodiment
19—secondary die plate of fourth embodiment

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring to FIG. 1 of the drawings, a modular die plate assembly is formed by the alternate juxtaposition of primary die plate of first embodiment 4 and secondary die plate of first embodiment 3 in a continuing sequence. A fiber-forming, molten, thermoplastic resin 1 is forced under extruder pressure into the slot 2 formed by primary die plate of first embodiment 4 and secondary die plate of first

embodiment 3. The molten thermoplastic resin 1, still under pressure, is then free to spread uniformly across the lateral cavity 6 formed by the alternate juxtaposition of primary die plate of first embodiment 4 and secondary die plate of first embodiment 3 is a continuing sequence. The molten thermoplastic resin 1 is then extruded in a fibrous form of molten thermoplastic resin 7 through the orifice 5 formed by the juxtaposition of the primary die plate of first embodiment 4 on either side of the slot 2 in lower surface of secondary plate 3. The size of the orifice 5 that is formed is a function of the width of the slot 2 and the thickness of the secondary die plate of first embodiment 3. A series of secondary die plates of first embodiment 3, each with a slightly different slot 2 shape, can also be used for a single orifice, resulting in an orifice 5 cross section which can be square, rectangular, elliptical, round or multilobal.

An alternative embodiment is shown in FIG. 2 wherein the modular die plate assembly is formed by the alternate juxtaposition of primary die plate 8 and secondary die plate 9 in a continuing sequence. A fiber-forming, molten thermoplastic resin 1 is forced under extruder pressure into the slot 2 formed by primary die plates of second embodiment 8 and secondary die plate of second embodiment 9. In this alternative embodiment the secondary die plate of second embodiment 9 is designed to contain two or more slots 2 communicating with the lower edge. These multiple slots 2 form a series of parallel lateral cavities 10 by the alternate juxtaposition of primary die plate of second embodiment 8 and secondary die plate of second embodiment 9 in a continuing sequence. The molten thermoplastic resin is then free to spread uniformly through the multiple cavities 6 and is then extruded in a fibrous form 7 through the multiple orifices 5 formed by the juxtaposition of the primary die plate of the second embodiment 8 on either side of the multiple slots in the lower surface of secondary die plate of second embodiment 9.

Referring to FIG. 3 of the drawings, a modular die plate assembly is formed by the alternate juxtaposition of the primary die plate of third embodiment 11 and the secondary die plate of third embodiment 12 in a continuing sequence. A fiber-forming, molten thermoplastic resin 1 is forced under extruder pressure into the slot 2 formed by primary die plate of third embodiment 11 and secondary die plate of third embodiment 12. The molten, thermoplastic resin 1, still under pressure, is then free to spread uniformly across the lateral cavity 6 formed by the alternate juxtaposition of primary die plate of third embodiment 11 and secondary die plate of third embodiment 12 in a continuing sequence. The molten, thermoplastic resin 1 is then extruded in a fibrous form 7 through the orifice 5 formed by the juxtaposition of the primary die plate of third embodiment 11 on either side of the slot in lower surface of secondary die plate of third embodiment 12.

To accommodate the flow of the drawing (attenuating) air or fluid 13, one or more separate and isolated channels 14 with slots 15 and exit orifices or nozzles 16 are placed laterally to each resin channel 17 in either the primary die plate of third embodiment 11 or secondary die plate of third embodiment 12, or both the primary die plate of third embodiment 11 and secondary die plate of third embodiment 12.

Referring to FIG. 4 a modular die plate assembly is formed by the alternate juxtaposition of the primary die plate of fourth embodiment 18 and the secondary die plate of fourth embodiment 19 in a continuing sequence. A fiber-forming, molten thermoplastic resin 1 is forced under extruder pressure into two or more slots 2 formed by primary die plate of fourth embodiment 18 and secondary die plate of fourth embodiment 19. The molten, thermoplastic resin is then free to spread uniformly across the lateral cavities 10 formed by the alternate juxtaposition of primary die plate of fourth embodiment 18 and secondary die plate of fourth embodiment 19 in a continuing sequence. The molten thermoplastic resin 1 is then extruded in a fibrous form 7 through the multiple orifices 5 formed by the juxtaposition of the primary die plate of fourth embodiment 18 on either side of the slot in lower surface of secondary die plate of fourth embodiment 19. To accommodate the passage of the drawing (attenuating) air or fluid 13, one or more separate and isolated channels 14 with slots 15 and exit orifices 16 are placed laterally to each resin channel 17 in either the primary die plate of fourth embodiment 18 or secondary die plate of fourth embodiment 19, or both the primary die plate of fourth embodiment 18 and secondary die plate of fourth embodiment 19.

The result is a matrix of air nozzles and melt orifices where their separation is a function of the slot design and secondary plate(s) thickness. The invention presents the ability to extend the air and melt nozzle matrix a virtually unlimited distance in the lateral and axial directions.

An alternative embodiment is shown in FIG. 5 wherein a single primary die plate is designed to serve as both the primary and secondary die plate by alternately reversing the primary plate to act as a secondary plate.

It will be understood that each of the elements described above, or two or more together, may also find a useful application in other types of constructions differing from the type described above.

While the invention has been illustrated and described as embodied in an extrusion apparatus with modular die units, it is not intended to be limited to the details shown, since it will be understood that various omissions, modifications, substitutions and changes in the forms and details of the device illustrated and in its operation can be made by those skilled in the art without departing in any way from the spirit of the present invention.

Without further analysis, the foregoing will so fully reveal the essence of the present invention that others can, by applying current knowledge, readily adapt it for various applications without omitting features that, from the standpoint of prior art, fairly constitute essential characteristics of the generic or specific aspects of this invention.

What is claimed as new and desired to be protected by Letters Patent is set forth in the appended claims.

We claim:

1. A disposable modular extrusion die body for extruding fibers from molten, synthetic, thermoplastic, polymeric resins comprising;

(a) a stack of alternating primary and secondary die plates;

(b) said primary and secondary die plate having :aligned top and bottom edges separated by no more than 0.15 meters;

(c) each of said primary and secondary die plates having a central opening there through, the central openings in said die plates communicating with each other to form a single continuous pressure equalization chamber within said die body extending through a central region of said die body;

(d) the top edge of each said primary die plate having an opening to receive molten polymeric resin, said opening communicating with said chamber permitting said

polymeric resin to enter said chamber wherein each orifice is equidistant from the feed manifold;

(e) a top surface of said die body wherein the total area of the openings on said top surface is at least forty percent of the total area described by the width of the opening and length measured across all of the primary and secondary die plates;

(f) the bottom edge of each said secondary die plate having an extrusion slot extending to said chamber, the adjacent primary die plates forming with said extrusion slot an orifice for the extrusion of said polymer resin.

(g) a means for delivering a stream of fluid adjacent each said orifice comprising a passage way extending the length of said die body passing through all of said die plates, and a channel in each said secondary plate from said passageway to and terminating at the bottom edge of said secondary plate in a nozzle for delivering said fluid adjacent the extrude resin;

(h) an equalization chamber segment formed by and within each combination of adjacent primary and secondary plates which has a volume of at least 2,000 times and no more than 40,000 times the volume of the orifice:

(i) a means to maintain the multiplicity of modules in sealed alignment with each other.

2. The disposable modular extrusion die body of claim 1 wherein the secondary die plate has more than one shaped slot providing communication between the pressure equalization chamber to the lower plate edge and provides a series of lateral orifices equal in number to the number of slots.

3. The disposable modular extrusion die body of claim 1 in which said nozzles direct the stream of fluid at the extruded resin leaving said extrusion orifice.

4. The disposable modular extrusion die body of claim 1 wherein the primary plates and secondary plates have identical cross sections and where the primary plate is alternately reversed to act as a secondary plate.

5. The disposable modular extrusion die body of claim 1 wherein the width of the secondary plate is at least 0.001 inches and no greater than 0.200 inches.

6. The disposable modular extrusion die body of claim 1 where the primary and secondary plates have means for extruding multiple molten fluids consisting of different polymeric resins.

7. The disposable modular extrusion die body of claim 1 wherein the polymeric resins used have an apparent melt viscosity in the die tip ranging from about 500 poise to about 3000 poise.

8. The disposable modular extrusion die body of claim 1 where the primary and secondary plates are formed from steel, copper, aluminum, nickel, titanium and their various commercial alloys.

9. The disposable modular extrusion die body of claim 1 where the length of the die body is greater than 0.1 meters.

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FORMATION OF SHAPED/MOLDED MELTBLOWING NONWOVEN STRUCTURES

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ABSTRACT

Three dimensional (3D) fiberweb structures are useful in many applications. The Robotic Fiber Assembly and Control System (RFACS) being developed in this research allows precise control of fiber meltblown fiber deposition on a 3D mold surface. The effect of various process parameters on a number of polypropylene (PP) web characteristics is reported. Under the experimental range studied, the fiber orientation distribution was significantly impacted by the process parameters. The fiber diameter distributions indicate that they are unique to a particular process condition. The distributions do not overlap when a parameter is evaluated. In keeping with the long-term objective of developing chemical/biological barrier fabrics using RFACS technology, the pore distribution of the fiberwebs was characterized. Under the conditions explored, the average pore size of the analyzing web has decreased by 60% when the attenuating air pressure was increased from 0.7 bar to 2.8 bar. The pore size was decreased by 33% when the take up speed of the web was increased from 20 ft/min to 50 ft/min.

1. INTRODUCTION

Nonwoven webs can be produced as sheet structures by using meltblown technology [23]. In meltblowing, molten polymer is extruded through a series of orifices in a knife-edge die. The die is jacketed on both sides by high velocity laminar sheets of air. The polymer streams from the orifices are elongated by the air-drag to form fibers, which are collected on a drum or other suitable collecting surface. Fiber diameters can range from 500 microns to as small as 0.1 microns (μm). The extreme entanglement of fibers, characterizing meltblown fibrous webs, produces coherency and strength. The density of the web is such that it has the property to contain and retain particulate matter [12], thus qualifying such structures for filtration applications. The entanglement of these long fibers makes it impossible to remove one fiber from the web or to trace one fiber from beginning to end [7]. Meltblown webs are lightweight with a high surface area. They display a high insulating value and excellent filter characteristics [3, 17]. Meltblown technology can be used to produce efficient filter materials, filtering particles that are bigger than 0.5 μm [24].

The long term objective of this research is to develop technology to produce shaped protective garments, substantially to its final shape and using minimal seaming or joining. The latter usually constitute the "weak-link" in a protective system. The integration of meltblowing technology and robotics can achieve the proper formation of molded or shaped seamless structure that may be incorporated in a protective clothing system. In integrating the two technologies the fiber web collector is usually a mold object structure. The mold can be manipulated to rotate continuously so as to form the molded fabric. The size of the die width should be smaller than the size of the mold to have a good control over the deposition of the fibers on the mold.

The usefulness of molded fabrics so obtained depends on the performance characteristics of the web structures. The desired performance characteristics, globally and locally, can be enumerated as strength, abrasion resistance, tear

resistance, burst strength, elastic recovery, air/moisture permeability, moisture/fluid absorption (rate and capacity), filtration characteristics, etc. Each of these characteristics is influenced by fiber diameter and its distribution, pore size and its distribution, fiber orientation, web consolidation (thickness, bonding), web basis-weight (local), fiber/polymer properties, etc.

The web structure defined by fiber Orientation Distribution Function (ODF) governs the anisotropy of mechanical (strength, tear resistance, bending rigidity, etc.) and physical (wicking/absorption, pore shapes, pore size distribution, etc.) properties [9-11, 13-15]. ODF data for meltblown webs has not been available in the literature previously, while some published ODF results for spunbonded fabrics are generally similar to those found for meltblown webs in this study.

Although meltblowing process produces finer fibers relative to conventional fiber spinning processes, the distributions of fiber diameter are usually quite broad. Because lower mean values and narrower distributions lead to smaller pore sizes (lower mean and narrow distributions) and higher specific surface, the control of fiber diameter distribution is considered highly desirable [18], for a number of important applications. The pore size and its distribution in a fabric structure are of prime importance in determining the transport properties of the fabric. The filtration efficiency, and hence the level of protection, is directly related to the pore size distribution. Image Analysis techniques have been developed to measure the pore size, shape, and orientation of the pores [23, 26]. Most of the methods developed at the Textile Research Institute (TRI) use fluid intrusion or extrusion on a sample to determine the average pore size and its distribution.

2. ROBOTIC FIBER ASSEMBLY AND CONTROL SYSTEM

To produce the seamless 3D garments a Robotic Fiber Assembly and Control System (RFACS) has been set up. The RFACS consists of a model meltblown machine and a commercial six-axis robot that is capable of manipulating the meltblown die in the range of positions and orientations required for use with the complex 3D shape molds. Accurate robot positioning is required to keep the distance between the die and the mold at will while maintaining appropriate orientations with the mold. In addition, to achieve the required level of mold control needed for this process, an external seventh axis has been added. The RFACS setup is shown in Figure 1.

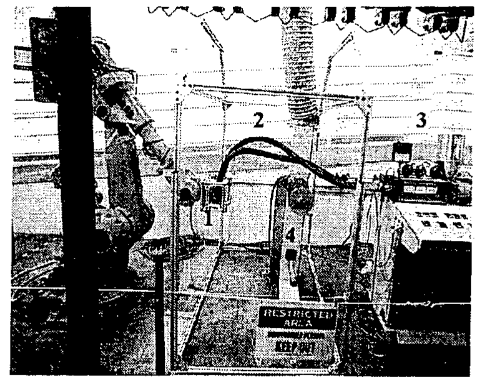


Figure 1. Robotic Fiber Assembly and Control System (RFACS)
1. Melt-Blowing Die Housed in a Cage.
2. Polymer and Air Flexible Supply Hoses.
3. Melt-Blowing Extruder Unit. 4. Collector.

The shaped nonwoven structures are produced by depositing meltblown fibers on a collapsible mold that is placed on the seventh axis of the robot. To develop the contour-following algorithms for mold shapes point coordinates on the mold shape were determined at regular rotational increments. To find these points in 3D-space for the 2D model, a pointer has been constructed such that the pointer tip assumes the virtual position of the right most orifice in the meltblowing die body. For the 3D model, a pointer mirroring the position of the polymer orifices has been constructed. The pointer uses to mark points on a mold relative to the world coordinate system. This procedure has been adopted as the means of developing the position and speed of the meltblowing die to the rotation of the mold body.

3. EFFECT OF PROCESS PARAMETERS ON WEB CHARACTERISTICS

The research documented in this paper deals with mold structures being coated with a meltblown web, hence, experiments were conducted to develop appropriate control algorithms. These algorithms would control the RFACS in a way to precisely control fiber dispensation on to the mold surface. The objective of the control algorithms is not necessarily to control uniformity of web characteristics, but to control

these locally. The web characteristics of interest in the context of the present research are (1) Basis weight, (2) Fiber orientation distribution, (3) Fiber diameter distribution, and (4) Pore size distribution. These characteristics determine the local physical, mechanical and fluid flow behavior of the web. The relevant process parameters are:

- Polymer throughput
- Die / Melt / Attenuating air temperature
- Attenuating air pressure,
- Fiber stream approach angle,
- Take-up speed, and
- Relative orientation and movement of die

In the following, the parametric studies are reported and categorized according to their influence on a specific web characteristics.

Basis Weight

The basis weight (g/m^2) of the PP fabric was evaluated by measuring the weight of known area of fabric samples at regular intervals, along the surface of the mold. The variation in measured basis weight is expressed as percent coefficient of variation (%CV). Initial experiments were conducted such that the die was moving up and down the mold, while the mold was rotating on the 7th axis at a uniform speed (2D no correction Model). The 2D model was modified to correct for variations in the die to collector distance (DCD correction) and the linear speeds of the mold on the 7th axis (linear rotational speed correction model).

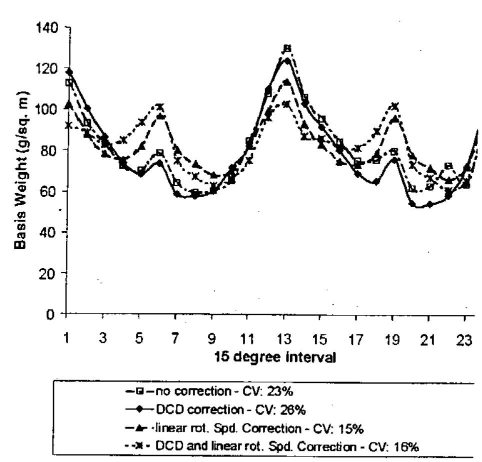


Figure 2. Two-Layer Basis-Weight Distribution Using the 2D Model

Figures 2 and 3 show the basis weight distributions using the patterns of motion variation for the 2D model. The differences in

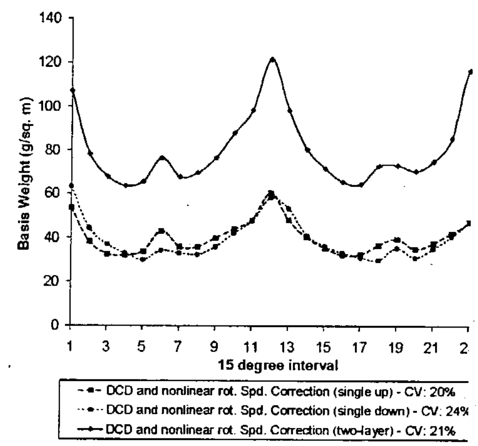


Figure 3. Single-Layer/Two-layer Basis-Weight Distribution using the 2D Model and Nonlinear Rotation Speeds

basis weight distributions are related to the interaction between the geometrical features of the mold and the characteristics of the fiber flaring profile and the die orientation. CV values for samples formed using the no correction model were 8% higher than CV values for samples obtained using the linear correction model. The difficulty in achieving more uniform basis weight distribution is inherently related to

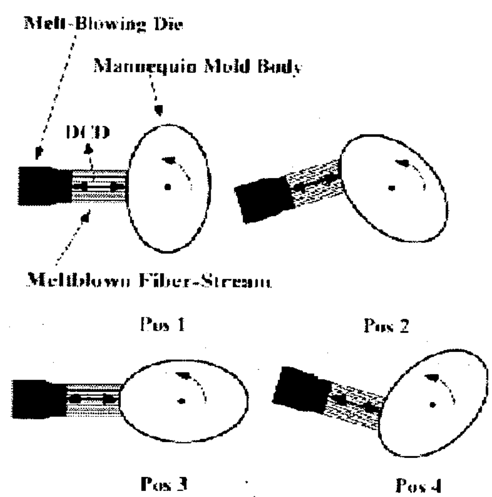


Figure 4. 3D Positioning Sequence

the die orientation during the production. When the die is not reoriented in relation to the surface of the mold during fiber application, overshot of fibers occurs. This causes loss of control for the deposition of fibers on the mold.

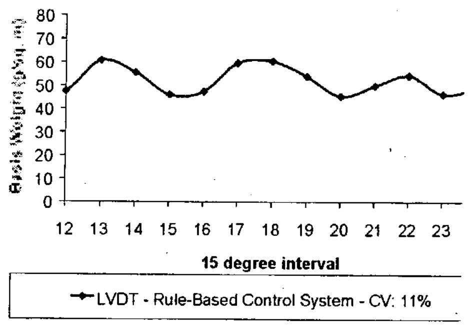


Figure 5. Rule-Based Control Results Using LVDT Feedback and 3D Triangularization

The 3D model was developed by the implementation of 3D-triangulation positioning and feedback control of the mold positioning data using the LVDT. This included the control of the movement of the die and the rotational speed of the mold mounted on the 7th axis (Figure 4). The position of the die is controlled such that the fiber streams are normal to the surface of the mold at the point of deposition of the fiber. A LVDT feed back control was used to control the speed of the 7th axis, such that the linear speed of the mold surface was constant. The overall control performance improved with the use of the 3D model [7]. Using the rule-based control resulted in the lowest overall CV values (11%) for basis-weight uniformity as it can be seen from the results of Figure 5. Since previous

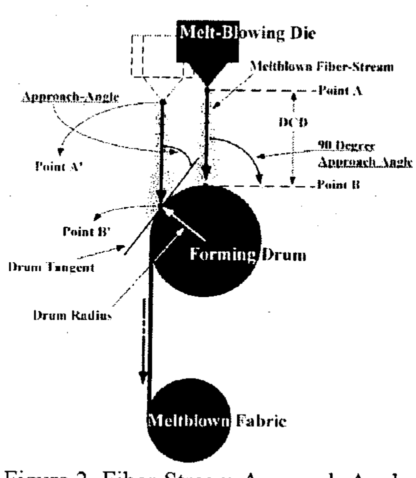


Figure 2. Fiber-Stream Approach-Angle

experimentation had shown basis weight effects to be symmetric around 180 degrees, only one side of the mold was evaluated.

Fiber Orientation Distribution

The orientation distribution function (ODF) of the fibers was measured on samples that were prepared using the 90^{o} fiber approach angle (Figure 6) relative to the collector drum. An image analysis package developed at the Nonwovens Cooperative Research Center was used to make ODF measurements on the samples. Influence of various process parameters on fiber orientation distribution is discussed below.

Take-Up Speed

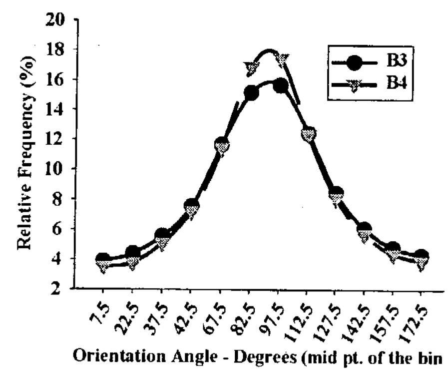


Figure 7. ODF for MB PP fabrics at different take-up speeds; 7 x 10^{-2} g/min/hole polymer throughput rate; 1.4 bar attenuating air pressure; 14 cm DCD and 282 °C air temp. ; B3: 18 m/min and B4: 24 m/min.

Figure 7 gives the ODF for fabrics formed at take-up speeds of 18, and 24 m/min, while other process parameters are held constant. Note that with extruder output kept constant the basis weight decreases with increasing take-up speed. The results show an increase in orientation with an increase in take-up speeds.

Maximum observed fiber fraction data along the machine direction (MD) in Figure 8, depicts increases in orientation along MD with increases in take-up speeds for all fabric types evaluated. Webs do not initially exhibit significant changes in its ODF at take-up speeds below 18.3 m/min. This may be due to aerodynamic interaction with

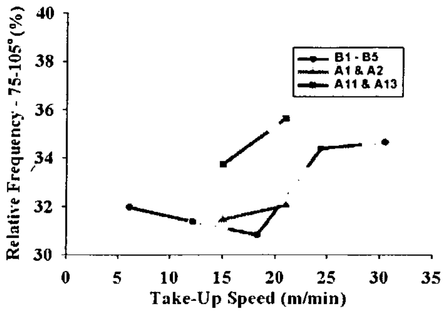


Figure 8. Maximum observed fiber fraction along "MD" for MB PP fabrics at different take-up speeds; 282 °C air temp.; B1-B5: 7 x 10^{-2} g/min/hole polymer throughput rate, 1.4 bar attenuating air pressure, and 14 cm DCD; A1 & A2: 5.4 x 10^{-2} g/min/hole polymer throughput rate, 1.4 bar attenuating air pressure, and 14 cm DCD; Ap11 & Ap13: 5.4 x 10^{-2} g/min/hole polymer throughput rate, 0.7 bar attenuating air-pressure, and 18 cm DCD.

fibers. For take-up speeds above 18.3 m/min fabrics show higher orientation due to higher drum surface velocity induced fiber alignment along the machine direction.

Die-to-Collector-Distance (DCD)

Figure 9 shows the ODF for fabrics formed at DCD settings ranging from 14 to 31 cm. Fiber orientation is shown to continuously increase from DCD settings 31 to 14 cm. All webs evaluated are shown to exhibit less MD orientation when formed at larger DCD settings. With longer distances the turbulent fiber flow, undulating, or flapping motion of the fibers is known to increase [6, 16]. As the air velocity reduces at longer distances from the die, and loses some of its initial planar characteristics, the air volume disturbed and the dimensions of the air stream increase [18, 19]. With higher freedom of movement, and lower fiber velocity the fibers appear to take on a more random orientation in the air stream. This effect subsequently translates to reduced MD orientation in webs formed, upon collection at larger distances (higher DCD settings) from the die body.

At a DCD setting of 7 cm, webs exhibited reduced "MD" orientation relative to those formed at 14 cm. This effect is attributed to some fibers being unable to successfully develop a forward flow pattern below DCD settings of 14 cm, and rapid successive, more random, accumulation of short segments of fiber on top of each other. Some fibers are suspected to be essentially blown into themselves, thereby causing less overall orientation in the structures formed. It is also stipulated that air velocities are still much higher at small DCD values, thus bouncing back from the forming drum and thereby disturbing the MD orientation of fibers.

Fiber-Stream Approach-Angle

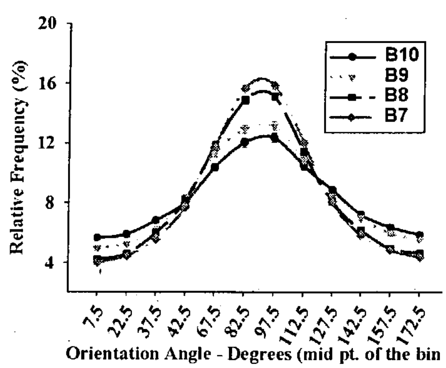


Figure 9. ODF for MB PP fabrics at different DCD; 7 x 10^{-2} g/min/hole polymer throughput rate, 1.4 bar attenuating air pressure, 21 m/min take-up speed, and 282 °C air temp.; B7: 14 cm; B8: 21 cm; B9: 26 cm; and B10: 31 cm.

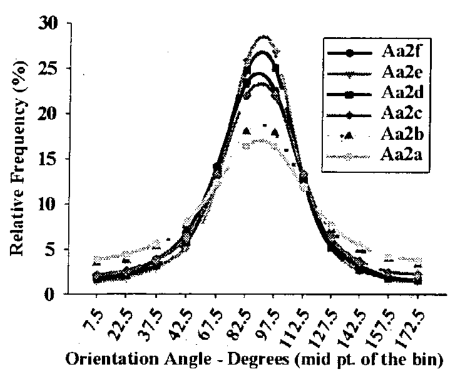


Figure 10. ODF for MB PP fabrics at different fiber-stream approach-angles; 5.4 x 10^{-2} g/min/hole polymer throughput rate, 1.4 bar attenuating air pressure, 21 m/min take-up speed, 14 cm DCD, and air temp. 305 °C; Aa2a: 90°; Aa2b: 79°; Aa2c: 61°; Aa2d: 46°; Aa2e: 36°; and Aa2e: 26□.

Figure 10, shows the fiber ODF for fabrics formed at approach-angles ranging from 90° to 26°. Fiber fraction along MD is shown to increase by 60 % when the fiber-stream approach-angle changes from normal to 36 °. A 0 ° approach-angle would identify a fiber-stream path parallel to the tangent of the fiber forming-drum (essentially blowing past it). By reducing the fiber-stream approach-angle, some fibers will travel a longer path before being collected on the drum's surface (see Figure 4). Those fibers, which travel a longer path, are also traveling at a path more parallel to the tangent of the forming-drum, and exhibit this orientation upon collection. This effect contributes to an increase in orientation in the machine direction. This pattern continues up to a point where some fibers are actually blowing past the drum, but are pulled back into the fabric because their fiber ends are anchored inside the fiber stream. This effect was visually observed when collecting samples at approach-angles of 26 °. Fibers were observed blowing past the drum's surface, but due to their continuous nature were still trapped inside of the fiber stream. This either caused them to stick out of the formed fabric, or to be pulled back into it. In either case the structure of the formed fabric was disrupted, which can be observed in the data shown by the respective decrease in fiber orientation at approach-angles of 26 °.

PolymerThroughput Rate

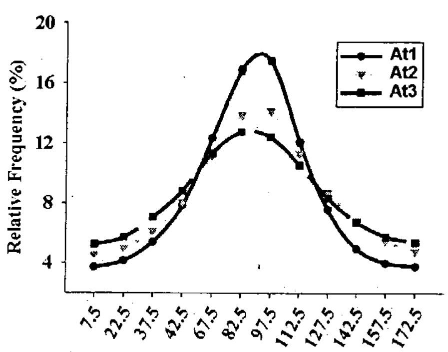


Figure 11. ODF for MB PP fabrics at different polymer throughput rate; 2.1 bar attenuating air pressure, 15 m/min take-up speed, 18 cm DCD, and 282 °C air temp.; At1: 5.4 x 10^{-2} g/min/hole, At2: 8.1 x 10^{-2}g/min/hole, and At3: 9.6 x 10^{-2} g/min/hole.

Fiber fraction along MD decreases with increasing throughput rate, as is shown in Figure 11. In meltblowing, analogous to what occurs in melt-spinning, higher polymer throughput rate is equated with larger average fiber diameter, keeping all other conditions constant [2]. When this is the case, larger size fibers present in the fiber stream will resist aligning themselves substantially in the air flow direction and assume a more random orientation. These fibers undulate more slowly (at lower frequencies) [16], as it becomes more difficult for a thicker and heavier structure to change direction as quickly as a smaller diameter structure. Lower undulating frequencies are shown to directly result in formation of more isotropic structures.

Attenuating Air Pressure

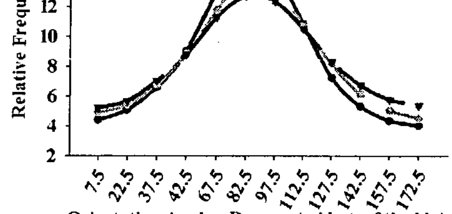


Figure 12. ODF for MB PP fabrics at different attenuating air pressures; 9.6 x 10^{-2} g/min/hole polymer throughput rate, 15 m/min take-up speed, 18 cm DCD, and 282 °C air temp.; Dp1: 0.7 bar; Dp2: 1.4 bar, and Dp3: 2.1 bar.

Figure 12 shows ODF results from fabrics formed by varying attenuating air pressure. Fabrics are shown to be less oriented along "MD" when higher attenuating air pressures are used. If one considers that higher take-up speeds have been shown to cause more orientation, the same argument can be made here. At lower attenuating air pressures the fiber speed reduces as compared to fiber formed at higher attenuating air pressures [25]. The ratio of take-up speed to fiber speed will increase with lower attenuating air-pressures. Subsequently an argument can be made that a decrease in fiber speed, i.e. lower

attenuating air-pressure, has the same effect as an increase in take-up speed, thereby causing higher orientation to form in the fabric structure.

Fiber Diameter Distribution

SEM images at 600X were used to make the FDD measurements. Each image contained at least 20 fiber images. A well developed protocol on the image analysis software was used for adjusting the SEM image [8]. The resulting black and white fiber image was evaluated for fiber diameter. Influence of various process parameters on fiber diameter distribution is discussed below.

Polymer Throughput Rate and Attenuating Air Pressure

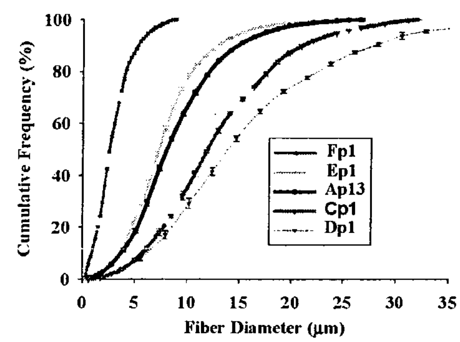


Figure 13. Cumulative frequency distribution of fiber diameters at different polymer throughput rates; 0.7 bar air pressure, 282 °C air temp., and 260 °C die temp.; Fp1: 1.7 x 10^{-2} g/min hole; Ep1: 3.7 x 10^{-2} g/min/hole; Ap13: 5.4 x 10^{-2} g/min/hole; Cp1: 8.1 x 10^{-2} g/min/hole; and Dp1: 9.6 x 10^{-2} g/min/hole.

Figure 13 shows cumulative frequencies of fiber diameter distributions of PP meltblown fabrics formed at different levels of polymer throughput rates and at a selected level of attenuating air pressure. Figure 14 shows cumulative frequencies of fiber diameters in fabrics produced at varying attenuating air pressure and a selected polymer throughput rate.

All web samples in Figure 13 show fiber diameters to decrease and their distribution to narrow with a decrease in throughput rate. Figure 14 shows cumulative frequencies for fiber diameter distributions in fabrics formed at varying attenuating air pressures, but a constant polymer throughput rate of 9.6 x 10^{-2} g/min/hole, and the same temperature settings as in Figure 13. Fiber diameters decrease with increase in attenuating air pressures in all cases; broader distributions of fiber diameters are observed with decreases in attenuating air pressures. All samples depict the same trend of increasing fraction of small diameter fibers with decreasing throughput rates; the increase in attenuating air

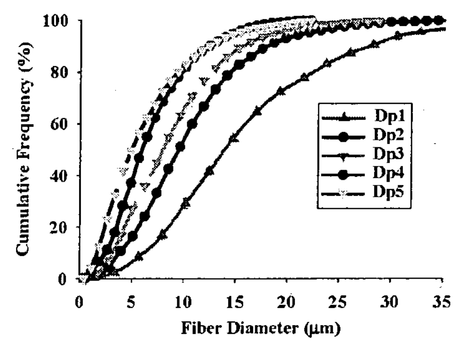


Figure 14. . Cumulative frequency distribution of fiber diameters at different attenuating air pressure; 9.6 x 10^{-2} g/min/hole throughput rate, 282 °C air temp., and 260 °C die temp.; Dp1: 0.7 bar; Dp2: 1.4 bar; Dp3: 2.1 bar; Dp4: 2.8 bar; and Dp5: 3.5 bar.

pressure also increases the fraction of fine (less than 10 µm) fibers. An increase in attenuating air pressure results in higher velocity of forming air, exerting higher drag forces on the polymer mass as it is being pushed out of the die orifices, as well as resulting in higher fiber velocities [2, 20]. Higher drag apparently attenuates the polymer mass to finer diameters, analogous to higher take-up roller speeds resulting in finer diameter filaments in conventional spinning.

Attenuating Air Temperature

Figure 15 shows cumulative frequencies for fiber diameter distributions obtained using varying attenuating air temperature. Fiber diameter was hardly affected by the attenuating air temperature in the range of (282 °C – 327 °C) studied. Similar trends were observed in a study by Rao and Shambaugh, where a 100^0 C increase in air temperature did not show much effect on fiber diameter [16]. In both Rao and Shambaugh and our case discussed, the polymer temperature (die temperature) settings were lower than the attenuating air temperature. The air temperature measured at the die orifice does not change significantly even when the employed die

temperature is lower than the air temperature. It is observed that the attenuating air temperatures studied in this research were not high enough to cause significant changes in diameters of the fibers.

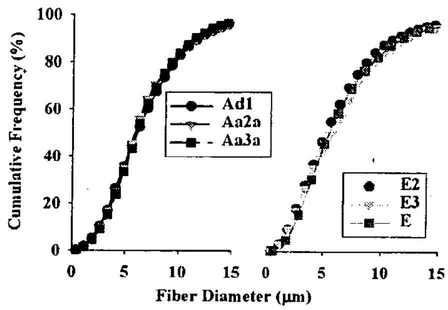


Figure 15. Cumulative frequency distribution of fiber diameters at different attenuating air temperatures; 5.4 x 10^{-2} g/min/hole throughput rate, 1.4 bar attenuating air pressure, and 260 °C die temp.: Ad1: 282 °C, Aa2a: 305 °C, and Aa3a: 327 °C; 3.7 x 10^{-2} g/min/hole throughput rate, 1.4 bar attenuating air pressure, and 260 °C die temp.: E: 282 °C, E2: 304 °C, and E3: 327 °C.

Die Temperature

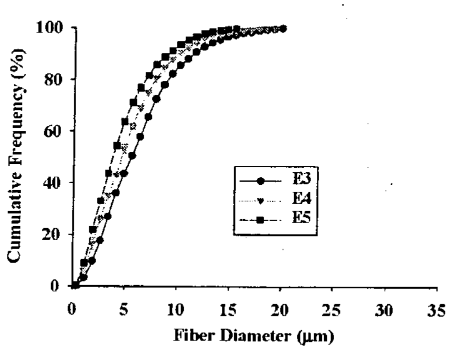


Figure 16. Cumulative frequency distribution of fiber diameters at different die temperature; 9.6 x 10^{-2} g/min/hole polymer throughput rate; 1.4 bar attenuating air pressure, and 327 °C attenuating air temp.; E3: 260 °C; E4: 293 °C; and E5: 327 °C die temperature.

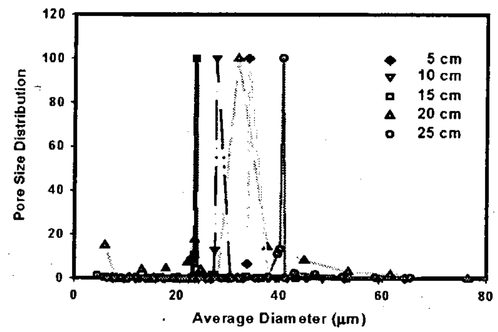
Figure 16 shows cumulative frequencies for fiber diameter distributions of PP meltblown fabrics formed due to varying die temperatures. As is apparent, fiber diameter decreased with increases in die temperature. All samples show increases in fine fiber content with increasing die temperature.

The dominant resultant effect of an increase in die temperature is lower polymer viscosity in the die body. A lower viscosity liquid will show less physical resistance to high velocity attenuating air, and allow finer fiber diameters to form. The reduction in polymer viscosity appears to be more significant over the temperature range evaluated, as similar changes in air temperatures have in this study not been able to show a lasting affect. Reduction in polymer viscosity would further show a larger effect at higher polymer throughput rates, where finer diameter fibers are formed with more difficulty.

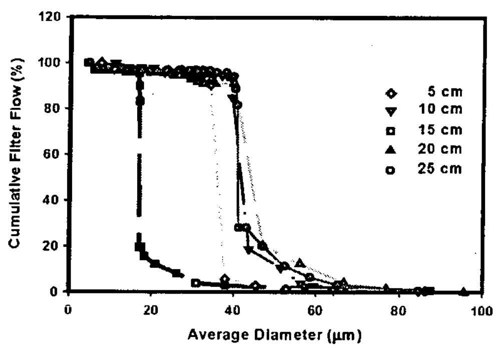
Pore Size Distribution

The pore size distribution was measured using an automated perm porometer designed and sold by the Porous Materials Inc. This equipment works on the principle of capillary flow. Details regarding the theory and the working principle of the instrument are found else where [8, 22]. Influence of various process parameters on pore size distribution is discussed below.

Die to Collector Distance



(a)



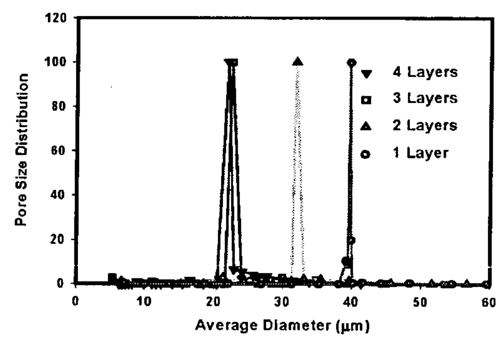
(b)

Figures 17 a & b. Pore Size Distribution and Cumulative Filter Flow (%) for MB PP Fabrics at different Die to Collector Distances. (Throughput : 3.7 x 10^{-2} g/min/hole, Air Pressure: 1.4 bar, Number of Layers: 2, Take Up Speed: 20 '/min)

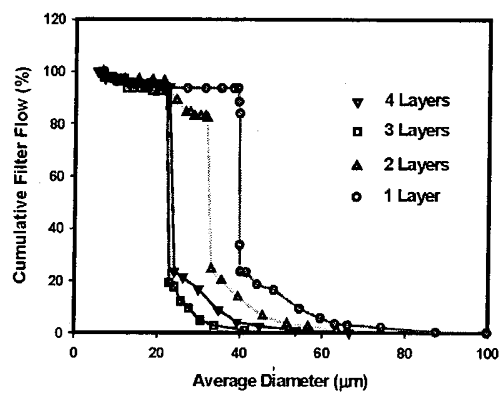
Figure 17 shows normalized pore size distribution and cumulative filter flow of PP meltblown fibers formed due to varying die to collector distances. The pore size initially decreases with increase in the distance. The diameter of the pore at 15 cm is 18 microns. At this distance the web has a filtration efficiency greater than 95%, and hence particles larger than 18 microns can be filtered. Further increase in the distance of the collector, increases the diameter of the pore. An increase in die to collector distance decreases the air velocity, alters the planar nature of the air, and the temperature of the air profile. It leads to the formation of shots and hence an increase in the pore size of the web.

Number of Layers

The Pore size distribution and the cumulative filter flow for the influence of the number of layers are given in Figure 18. These graphs indicate that with increase in the number of layers the pore size decreases and the filtration efficiency increases. The technique adopted measures the smallest diameter of a given pore and thereby if a layer of fibers with relatively small pore size distribution is incorporated in the web, the overall pore size becomes smaller. With the decrease in the average pore size, the filtration efficiency increases. The data further indicates that increase in the number of layers from three to four does not have a significant effect on the pore size distribution and the filtration efficiency.



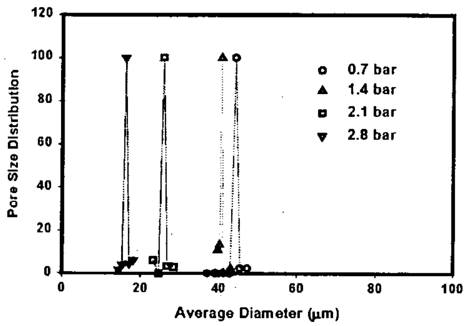
(a)



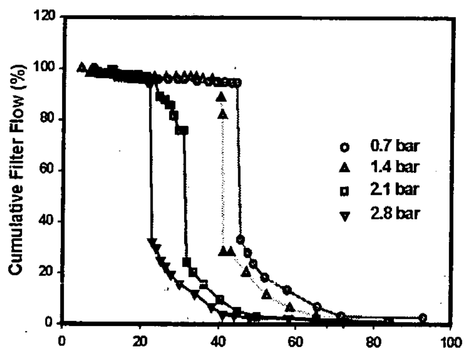
(b)

Figures 18 a & b. Pore Size Distribution and Cumulative Filter Flow (%) for MB PP Fabrics for variation in the number of layers. (Throughput : 3.7 x 10^{-2} g/min/hole, Air Pressure: 1.4 bar, DCD 15 cm, Take Up Speed: 20 '/min)

Attenuating Air Pressure



(a)

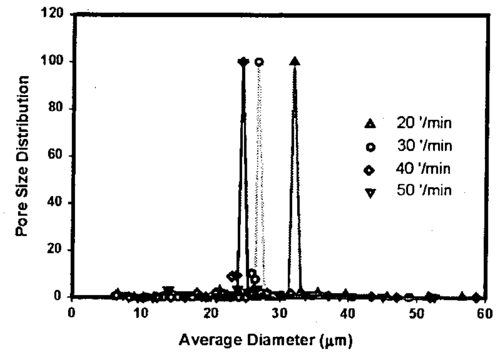


(b)

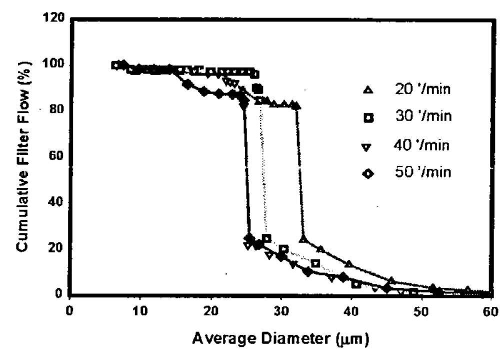
Figures 19 a & b. Pore Size Distribution and Cumulative Filter Flow(%) for MB PP Fabrics for variation in the attenuating air pressure. (Throughput : 3.7 x 10^{-2} g/min/hole, Number of Layers: 2, DCD 15 cm, Take Up Speed: 20 '/min)

As was mentioned in our earlier discussion, with increasing attenuating air pressure the fraction of smaller fibers increases. An increase in the attenuating air pressure results in an increase in the velocity of the forming air and hence, an increase in the drag force exerted on the fiber. This leads to the formation of fine fibers. Finer fibers produced arrange themselves closer together and hence finer pores are formed in the web. Figure 19 shows the pore size distribution and the filtration efficiency of the webs produced at different attenuating air pressures. Complementing the pore size distribution, the filtration efficiency increases with increasing attenuating air pressure. A higher percentage of finer pores increase the filtration efficiency of the web [1, 4, 5].

Take-Up Speed and Through Put



(a)

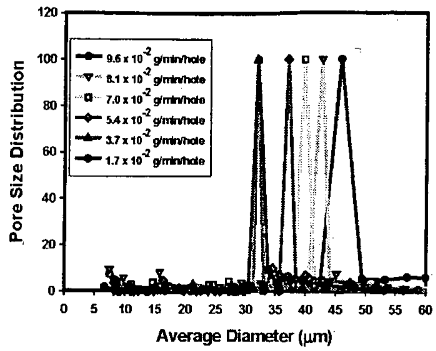


(b)

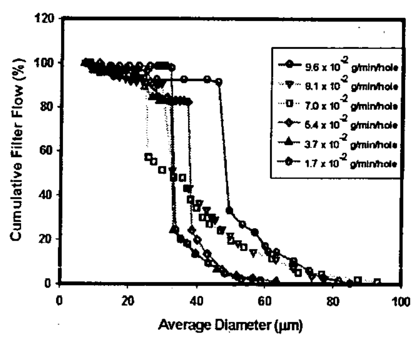
Figures 20 a & b. Pore Size Distribution and Cumulative Filter Flow(%) for MB PP Fabrics for variation in the web Take up Speed (Throughput : 3.7 x 10^{-2} g/min/hole, Number of Layers: 2, DCDC: 15 cm, Air Pressure: 1.4 bar)

As has been mentioned in the earlier discussions, increase in the take up speed of the web decreases the basis weight of the web. The increase in take up speed also increases the fiber orientation in the machine direction. The increase in the orientation in the machine direction and the decrease in basis weight due to increase in the take up speed decreases the average pore size and forms a narrower distribution, as also reported by Bhatia [4]. As is shown in Figure 20, the increase in take up speed decreases the pore size and increases the filtration efficiency of the web. But, at the current throughput rate, basis weight and

attenuating air pressure there is no change in the pore size and filtration efficiency when the take up speed is changed from 40 ft/min to 50 ft/min.



(a)



(b)

Figures 21 a & b. Pore Size Distribution and Cumulative Filter Flow (%) for MB PP Fabrics for variation in the Polymer Throughput (Take Up Speed: 20'/min., Number of Layers: 2, DCD: 15 cm, Air Pressure: 1.4 bar)

Figure 21 shows the pore size distribution and filtration efficiency of the webs for different throughput levels. Similar to the influence of through put on the diameter distribution of the fibers in the web [8], the average diameter of the pore size of the web decreases with the decrease in the through put through the meltblowing system. The diameter distribution range decreases. The filtration efficiency of the webs increases with the decrease in the average diameter of the pore size.

4. CONCLUSIONS

A novel 3D fiberweb manufacturing technology has been successfully developed. This Robotic Fiber Assembly & Control System (RFACS) can be implemented for production of seamless 3D meltblown nonwoven fabric structures. The set-up developed here allows for arbitrary positioning of the melt-blowing die in an initial reference frame to an arbitrary collecting surface without difficulty and accuracy of 1/10 of a millimeter.

Experiments have demonstrated that rotational motion of a mold needs to be controlled according to its shape (curvature, etc.), when uniform basis-weight distribution is required. Various motion correction models (i.e. linear and nonlinear) may be successfully employed to some extent. Relative movement and orientation of die and collecting surface must be considered carefully to achieve desirable results. For the case of fiber deposition on a mold, it is desirable to have the center of the tool carrying die aligned normal to the surface of the mold. Such an orientation allows for more uniform fiber application to the mold surface and results in a 4%-10% improvement in basis-weight uniformity. Implementation of a rule-base control algorithm that compensates for the mold position and speed as well as tool position was successfully done. The approach improves the basis-weight uniformity and significantly simplified the robot programming operation.

Fiber ODF is shown to be a useful parameter for detailed analysis of changes taking place in meltblown nonwoven structures. Changes induced in structures by variation of process parameters were appropriately related to respective changes observed in the fabric's ODF.

Changes in fabric take-up speed, die-to-collector-distance, fiber-stream approach-angle, polymer throughput rates, and attenuating air-pressures were shown to significantly affect fiber ODF in webs. Generally all fiber ODFs exhibited a bell-shaped pattern, with the highest frequency of orientation in the vicinity of MD. Changes in fiber-stream approach-angles were demonstrated to affect respective changes in fiber orientation distribution to the highest extent. For a change in fiber-stream approach-angle from normal (90°) to 36°, a 60 % increase in fiber alignment along the machine direction was shown.

Fiber diameter distributions were shown to correlate well to processing conditions employed in meltblowing of polypropylene resin. Fiber diameters were demonstrated to reduce with reductions in throughput rate, and increases in

attenuating air pressures and die temperatures. Air temperatures in the range studied, below 210 °C at the die-orifice exit, were shown to not affect fiber diameter distributions. Good agreement for all results was also found to average fiber diameter data observed in published literature.

The pore size distribution and the filtration efficiency of the melt blown polypropylene webs were characterized. The effect of the process variables on the average pore size distribution was investigated. The changes in the average pore diameter were related to the diameter changes that take place in the fibers formed and their orientation distribution. The change in die-to-collector-distance, number of layers, attenuating air pressure, polymer throughput rates, and web take up speeds were shown to significantly affect the average pore size and the filtration efficiency of the webs formed. In the case of die to collector distance, the least pore size and the best filtration efficiency was formed at a distance of 15 cm. as the temperature of the attenuating air is dropped to around temperature beyond the 15 cm. This does not allow further changes in the internal structure of the fiber and also effects the consolidation of the fiber web on the collecting surface. The increase in attenuating air pressure from 0.7 bar to 2.8 bar reduces the average predominant pore size by 60%, while when the take up speed is increased from 20'/min to 50'/min, the average pore size reduces by 33%.

ACKNOWLEDGEMENTS
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A Review of the Melt Blown Process

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ABSTRACT

The melt blown process produces a fine fiber, small pore size, nonwoven web directly from polymer chips. The web is formed entirely of a given polymer without the need of added binders, finishes or thermal bonding of the fibers. A variety of additives can be put in with the polymer to affect the end properties of the web; similar to any other extrusion based process. The web can undergo further processing such as calendering to produce finer pore sizes. These webs have been found to be useful as a battery separator, especially in alkaline chemistries. This paper gives a general review of the process.

History

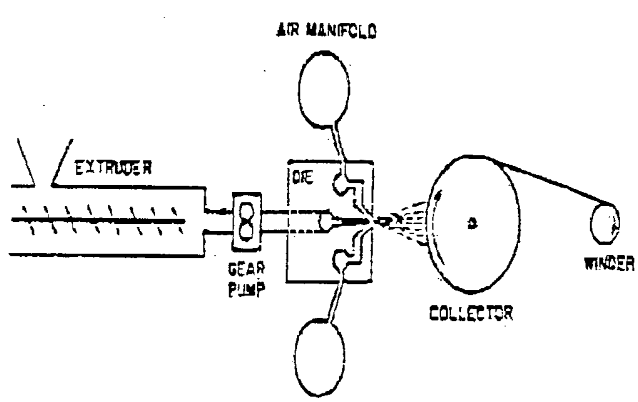
Melt blown technology was initially developed under the sponsorship of the United States government in the 1950's. The work was begun at the Naval Research Laboratory for the collection of radioactive particles in the upper atmosphere. In 1954 Van A. Wente was the first to demonstrate the concept of melt blowing of molten thermoplastic resins to form microfibers of less than 10 microns (1, 2,3). During the 1960's Exxon Research and Engineering (then Esso) developed the equipment to produce a continuous web 40-inch wide. The initial development work was for battery separators (flooded lead acid) and synthetic electrical paper. Exxon developed a 3-ply calendered Polypropylene (PP) laminate for this application (4). Reigel Products commercialized a PP melt blown Separator for lead acid, maintenance free SLI batteries in the 1970's. Problems with uniformity, re-wetability (hydrophobic nature of PP) and fabric abrasion slowed its acceptance and led to the demise of the product (5). Exxon recognized potential use in filtration, hygiene products, adhesive webs, cigarette filters and specialty synthetic papers. They also recognized the possibilities of combining melt blown webs with other webs, especially for reinforcement, through laminations and coatings (6). Exxon built an extensive patent position for melt blown. During the 1970's, Exxon began licensing this technology and continued to support research at the University of Tennessee. Today, the University of Tennessee (TANDEC) has assumed licensing of the technology. There are over 45 active licensees of the melt blown process. Melt blown production accounts for about 5% of the total worldwide production of nonwovens however it accounts for about 30% of the total patent activity in nonwovens (7). Numerous melt blown battery separator patents abound for all battery chemistries.

Description of Melt Blown Process

The melt blown process is defined as a one step process. The thermoplastic resin is melted in an extruder, passed through a circular orifice, drawn by the impingement of high velocity, hot air into fine fibers, which are collected onto a belt or drum, forming the nonwoven web in one operation.

In most cases, the die tip consists of a single row of holes extending across the width of the machine. These holes are approximately 300 micron in diameter and Spaced at 2 to 16 holes per cm width of the die. A metering or gear pump is used after the extruder to insure uniform and consistent delivery of the molten polymer. The molten polymer is fed to this row of holes, by a coat hanger die, similar to those found in film extrusion.

Figure 1. Simple diagram of melt blown process (8).

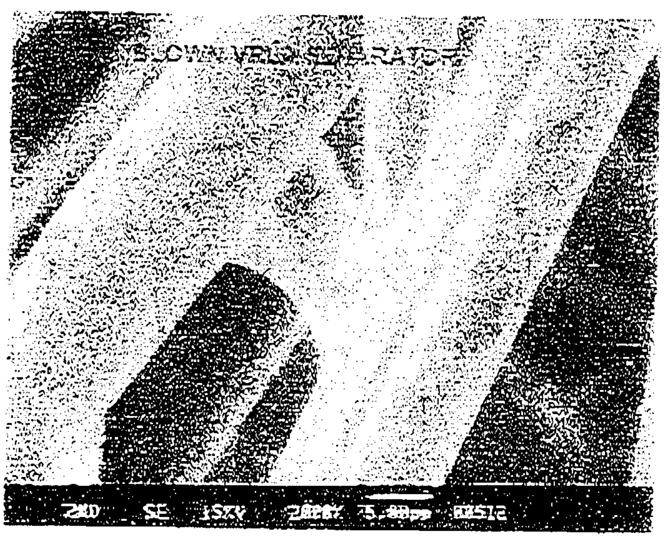


0-7803-5924-0/00/$10.00 ©2000 IEEE.

The hot air is divided into two channels that impinge on the molten fiber as it leaves the die tip, figure 1. The fibers within an inch of the die tip are attenuated down to a fiber diameter between 2 and 10 microns average fiber diameter. At this distance the velocity of the hot air approaches sonic velocity. The hot air jet entrains ambient air and expands as it passes from the die tip, which allows the fibers to cool before collection as a web. The web is typically collected under suction and the fibers obtain a random orientation on lay down as well as becoming entangled.

Quite often melt blown webs are simply wound up and used as is. They often go through finishing operations. These operations include electrostatic charging to improve particle filtration from air or other gases, calendering to reduce thickness and lower the pore size and lamination to other substrates. They are often combined with spunbonds (SMS) or extruded nettings for improved strengths or improved abrasion resistance. Lamination is most often done with heat or ultrasonics making use of the thermoplastic properties of the polymers.

Figure 2. Melt blown separator that shows graphed fibers for improved wetting of the separator. The treatment is indicated by the irregular surface of the fibers.



The polyolefin webs are inherently hydrophobic. To improve wetability of the web various surface treatments must be done to the fibers such as treatment with surface active agents, sulphonation (9) or grafting functional groups on to the fibers with UV to add functional groups to increases the hydrophilic nature of the web, figure 2.

Web Characteristics

The fibers formed in the process are generally considered as being continuous with a random orientation. Since the fibers are stretched when molten and then rapidly quenched, there is low crystallinity in the bulk of the fiber which leads to a weak fiber. This combined with entanglement of the fibers results in a relatively weak web. However, the fine fibers provide good coverage and therefore have low opacity. The fine fibers and good coverage provide a tortuous path through the thickness of the web so that melt blown webs have low pore sizes when compared to other nonwovens such as spunbonds, but larger when compared to separators such as microglass AGM for VRLA batteries.

The microfibers provide a high surface area, which is an important characteristic for insulation and filtration. The fibers have a generally smooth surface texture and are circular. There is a high degree of fiber branching or bundling which is a result of molten fibers contacting each other near the die tip.

Another web defect associated with melt blown is known as shot, which are clumps of polymer. These clumps are a result of equipment cleanliness as well as the process conditions. Shot is generally attributed to the breakage of the fibers as they are being drawn in the air stream.

Most melt blown webs have a layered structure due to the circular motion of the fiber going onto the collection belt. This layered effect is more pronounced in heavier webs. Since the surface fibers are bonded minimally, melt blown webs are considered to have low abrasion resistance. However, since the fibers are essentially continuous melt blown webs should be considered not to have shedding fibers.

Melt blown webs can be made in a variety of basis weights by controlling the extrusion rate and the speed of the collection device. Webs can be made as light as 5 gm^{-2} unsupported or below 1 gm^{-2} with a support web. Webs can be made as heavy as 400 gm^{-2}.

Average fiber diameters for a melt blown web can range from 2 to 20 microns. This is still higher than the fiber diameters that can be obtained with microglass separators or membranes. Any melt blown web due to the randomness of the hot air, high velocity, fiber attenuation process has a rather broad distribution of individual fiber diameters, similar to the distribution in a microglass VRLA separator. For example, microscopic examination of a 3-micron average web will show fibers below 1 micron as well as fibers up to 10 micron.

Another difference between a wet laid separator such as a microglass and a melt blown separator is that the melt blown process does not produce as uniform a web as does the wet laid technology. A good melt blown process may have a uniformity of ± 10% while a wetlaid process can deliver in the ± 4% range. This can have critical negative performance influences in systems such as VRLA batteries where compression force on the active material is crucial to long term battery performance.

The average fiber diameter is mainly determined by the throughput rate however other factors such as melt temperature melt viscosity, air temperature and air velocity also affects the fiber diameter.

Melt blown parameters can also be adjusted so as to produce a wide range of web densities. The throughput, temperature and collection distance will affect the web density. Web densities can be made as low as 0.1 gcm^{-3} or as high as about 0.15 gcm^{-3}. If the web goes through a subsequent calender step, densities as high as about 0.8 gcm^{-3} can be made. At an equivalent density a polyolefin web will have a lower porosity to absorb electrolyte as compared to a microglass media. This is due to the lower density of the raw materials typically in the 0.9 to 1.1 gcm^{-3} as compared to microglass at 2.5 gcm^{-3}.

Polymers

Theoretically, any thermoplastic polymer should have the ability to be meltblown, however some polymers definitely work better than others do. Most melt blown materials are made with polypropylene due to intrinsic properties as well as cost and the versatility to make a wide range of products from very fine to very coarse fibers. The next most used polymers are probably polybutylene terephthalate and Nylon 6. Both are fairly easy to process but are more expensive than polypropylene. Other polymers that have been melt blown include linear low-density polyethylene, Nylon 6,6 and 12, polycarbonate, polyphenylene sulfide, polymethyl pentene, polystyrene, polyethylene, and polyvinyl alcohol. Some co-polymers that have been melt blown include ethylene/ chlorotrifluoro-ethylene, copolyesters, polyurethan, ethylene vinyl acetates and polyamide polyethers.

Since the molten fiber must go through a substantial draw down over a very short distance, the polymer must have a low melt viscosity at the process temperature. One common industry measurement for melt viscosity is Melt Flow Rate (MFR). This is the amount of polymer, in grams that flows through a given orifice under a given load at a given temperature in ten minutes. A high MFR translates into a low melt viscosity. A typical polypropylene used for melt blowing would have an MFR of about 1000g/10 minutes. This roughly corresponds to a melt viscosity of about 50 poise. For comparison, polypropylene resins used in extruded fibers are about 150 MFR while a commodity polypropylene for a molded part would have an MFR below 10. The higher MFR resins also allow for lower processing temperatures which reduce polymer degradation and the life of the equipment.

Additives

Although one of the advantages of melt blown webs is that the fibers can be made from a pure polymer, many additives can be added to improve the performance of the web. The additives are typical of other extrusion processes. Most do not affect the fiber production if they are kept to levels below 5 to 10%. Most additives are most easily processed if they first are made into concentrate with the primary resin. Typically these concentrates are made as pellets containing 10 to 20% of the additive. They are then mixed with virgin resin to get the level down to around one- percent and then fed into the extruder. Use of the concentrates makes feed into the extruder easier and also helps to insure a uniform mixture of the additive.

Additives would include:

- Pigments
- Lubricants
- Flame Retardants
- Wetting Agents
- Anti-Oxidants
- Light Stabilizers
- Heat Stabilizers
- Anti-Stats

Quite often peroxides are added into polypropylenes to achieve the high MFR's discussed above. The peroxides controllably cut the polymer chains without affecting other properties of the polymer.

Applications

Exxon accurately predicted current uses for melt blown webs over 25 years ago. The melt blown process uniquely produces fine fiber webs not available in other technologies with the exception of wet laid microglass. The following markets currently use melt blown products:

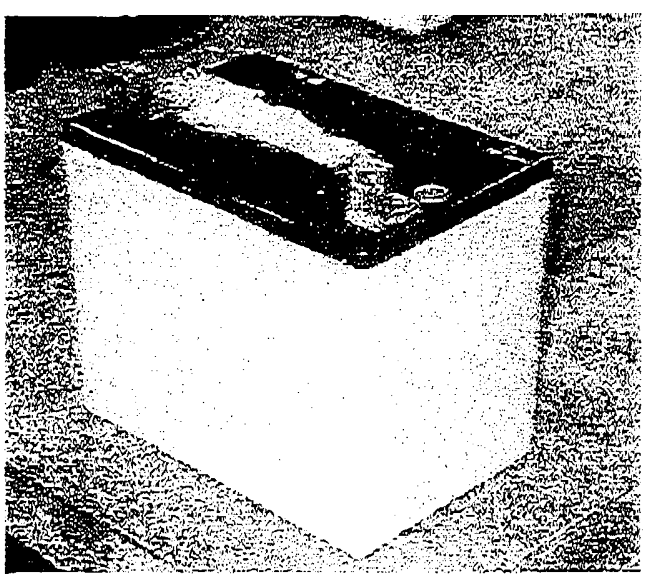
- Medical Fabrics- OR gowns, drapes and face masks
- Filtration Media- HVAC, liquid filters, industrial face masks, vacuum cleaner bags, indoor air quality, bag filters, blood filters.
- Sanitary Products- Infant diapers, feminine hygiene.
- Waste Sorbents- Oil booms, industrial spills.
- Wipes

- Hot Melt Adhesives
- Electronic Specialties- Battery Separators, Cable Wrap

Meltblown Webs as Separators

The melt blown process was originally targeted to capture the large automotive SLI lead acid market for maintenance free batteries. The technology as compared to other separators for this market, microporous polyethylene and 10-G, proved not to be a suitable technology. This was due to the separator's relative higher cost, poorer oxidative resistance, poor uniformity and the hydrophobic nature of the thermoplastic materials used to extrude the fibers. Althougn, the melt blown technology has improved, since the 70's, allowing for a more uniform product today, so has the other competing technologies, i.e., such as thinner backwebs for microporous polyethylene separators. The technology to make the fibers hydrophilic has also drastically improved but still does not allow for the long-term hyrophillicity in lead acid separators systems for lead acid batteries. Surface treatments to polyolefins have been very successful for use in alkaline electrolyte applications. In lead acid the same applications have still been problematic.

Figure 3. Foaming VRLA Battery



In a recent battery test using a commercially available melt blown separator the lead acid batteries suffered from thermal runway, short cycle life (about 50 cycles) and foaming from the vent valves, figure 3. Control batteries using 100% microglass separators had none of these problems. The control batteries had 7 times the cycle performance of the melt blown separator batteries, without any of the safety problems observed during the testing. The melt blown batteries during testing had forty percent of the batteries go into thermal runaway. Tear down analysis of these batteries showed that the separator was hydrophobic in random areas. Some cells had considerable amount of free acid on the top of the cell. It is assumed this free acid on the top of the cell was boiling to the top of plates in the cell, as the separator became more hydrophobic. The separator would not absorb this free acid, even though it was observed that numerous dry area/spots within the cell group. Testing of these spots outside the cell verify that the separator was repealing the acid.

On the other hand, melt blown separators for alkaline and lithium technologies are the systems that have seen the main benefit from the melt blown technology. Commercial melt blown separators are being used in lithium, nickel cadmium and nickel metal hydride systems and other battery systems.

Since the melt blown process extrudes the fibers in one step, the process can provide a separator with overall finer fibers to provide greater coverage. The melt blown technology can provide a fiber with an average fiber diameter down 1-2 microns. A typical staple fiber used in the nonwoven process start at 12 microns. Therefore, the surface area of a typical melt blown is higher than a staple fiber nonwoven separator. This results in a finer pore structure and greater tortuousity, at an equivalent thickness for the separator.

However, the weight uniformity of a melt blown as compared to a traditional drylaid staple fiber nonwoven is more variable. The other drawback of melt blown is lower strength and lower compression rebound. In fact resiliency of a melt blown separator is so poor that it actually seals off the separator. This is why 100% melt blown separators are rarely used in cylindrically wound cells. On the other hand surface treatment of polyolefin melt blown is particularly effective due to the high surface area.

Strength issues have been addressed by laminating, to either one or both sides, other types of nonwovens, such as spunbond webs to the melt blown base material. This approach improves uniformity and strength related processing issues. However, the laminate tends to reduce surface area and increases nonporous areas leading to an increase in electrical resistance and in some cases higher internal cells impedance.

Overall, as this technology matures further the melt blown process will continue to expand the benefits to the battery community by allowing for improved separator systems.

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